Investigations on Opportunistic Networking Mechanisms in IEEE 802.15.4-based wireless mobile body sensor networks

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I dedicate this thesis to my parents, Nasir Ali Chaudhry and Attia Ali, who are my biggest supporters in all my adventures, my husband, Muhammad Tahir Chaudhry, who supported me throughout this time, my beloved children Muhammad Hamdan Tahir and Rida Tahir, my lifelines who are a great source of joy through the difficult times and a special dedication to my heavenly child Muhammad Hassan Tahir who will live in my heart forever.

Abstract

Neighbour discovery and message scheduling are two very important functions of wireless networks. This thesis explores these two domains of wireless networks. The first part of this work investigates the passive discovery of IEEE 802.15.4-based Body Sensor Networks (BSNs). The later part focuses on message scheduling in Opportunistic networks.

Wireless body sensor networks is an important research area in the field of health care. These networks aim to improve the well being and quality of life. BSNs are wearable networks that can monitor the vital functions of the body and alert the concerned health practitioners in case the status of any of the vital functions is abnormal. Since, these networks are wearable, they allow the person to roam around freely without having to deal with the clutter of the cables.

One challenging task that BSNs has to perform is to discover the target network or the coordinator nodes. This target network or the coordinator node can be a gateways where the BSN coordinator offload data for further processing and storage services.

This thesis presents a cooperative passive discovery scheme (the rumour-based scheme) for the beacon-enabled mode that is based on a simple class of listening strategies called sweep strategy for IEEE 802.15.4 based body sensor networks. The thesis investigates a simple scenario of unbounded targeted discovery where a specific mobile BSN is searching for a specific destination network. The performance of this scheme is evaluated in terms of the average discovery time using simulations. The results show that this scheme can significantly reduce the time required to discover the target network.

The next part of the thesis focuses on the a message scheduling algorithm for opportunistic network or Delay Tolerant Network (DTN). Opportunistic networks are characterized by having only intermittent connectivity on end-to-end paths due to highly mobile nodes. Due to this mobility,a successful delivery of messages becomes a real challenge for these network.

Message scheduling is a key part of an opportunistic routing and forwarding scheme. A node has needs to find the sequence in which it transmits messages reliably for further relaying to its various neighbours.

This thesis presents a scheduling scheme that incorporates the knowledge about the *remaining contact time* into the scheduling. The scheduler sorts the messages according to their priority and sizes. When a node comes in close contact with other node, the scheduler then messages are then sent while taking into account the remaining contact time left between the nodes. The performance of thesis scheme is compared against baseline schemes from the literature.

The results show that incorporating remaining contact time can indeed give substantial improvements in key performance indicators like the average delivery delay or the overhead ratio.

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Acknowledgments

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Chapter I

Introduction to Wireless Body Sensor Networks and Opportunistic Networks

1.1 Wireless Sensor Networks (WSN)

Wireless sensor networks comprise a group of small devices that usually are deployed for monitoring different physical phenomenon. WSN consist of sensor devices that are small, low powered and energy efficient often called "nodes". These sensor nodes connect to each other to form a network. These networks are characterised by a large number of nodes that occupy a vast geographical area. However, the size of the WSN and the network topology (single-hop, multi-hop or mesh topology) depends upon the type of application.

With the development of wireless sensor network technologies and cost reductions of sensor devices, wireless sensor networks have found application in almost every field of life. Some of the applications include:

- **Military Applications** Sensor networks have a wide spread use in many military related application for information capturing, advancement in warfare and field [25]

- **Environmental Monitoring** WSN are being used for environmental protection [14] and monitoring, for example, in green houses for micro environment control [29]

- **Mine Monitoring** The data collected by the sensors inside the mines is used to develop efficient mine monitoring system[23]

- **Agriculture and Forestry** WSNs are helping farmers in improving the irrigation by predicting the crop water requirements [26]

- **Intelligent transportation system** WSNs are also being used to develop intelligent transport systems [48]

1.1.1 Wireless Body Sensor Networks (WBSN)

The first part of the thesis is discuss *wireless body sensor networks* which are an important application of WSN is the monitoring of health and vital functions of a person. This special class of sensor networks is known as Body Area Networks or Body Sensor Networks (BANs or BSNs) [11], [63], [42]. The idea of BSNs emerged from Wireless Personal Area Networks (WPANs) around 1995. BSNs consists of small wearable sensor nodes attached to the body of the person where they collect data from different body functions. The main objective of the BSN is to improve the quality of life by constantly monitoring the important functions of the body. For instance, for a patient, who is seriously ill, BSN can constantly monitor the functions without the physical presence of a caregiver. On of the main advantages of BSNS is that BSNs give people independence to move freely while their vital signals are being monitored.

BSNs are similar to WPANs and fixed sensor networks but there are also considerable differences [66]. WSN are large in size and have a huge number of nodes that are deployed over a large geographical area[33] [56]. While, BSNs extend only over small geographical areas (dimension of human body) typically have a small number of nodes[40]. The most commonly used topology used for such networks is star topology where the sensor nodes are at a single hop distance from the coordinator [20].

A distinct feature of BSNs is that they move as a whole in a group, together with its human carrier. Such mobility is also called *Group Mobility*[12] [41]. IEEE 802.15.4 standard is a Low-Rate Wireless Personal Area Network (LR-WPAN) [40].

There are many candidate network technologies available for implementing BSNs, for example the recently approved IEEE 802.15.6 standard [39] [28]. This standard specifically designed for the WBSNs and the compatible hardware is available commercially. However, to the best of out knowledge, when the experiments for this work were conducted, there was no hardware compatible to this stndard was commercially available. Therefore, we considered the IEEE 802.15.4 standard [39] as our baseline, because it is a well-established standard and the commercial availability of cheap and mature component suggests that it will also remain a serious contender for BSN applications for quite some time to come. The standard aims to provide a low cost and simple implementation for WPAN applications. This standard provide specifications for Physical (PHY) and Medium Access (MAC) Layer.

1.2 Opportunistic Networks

The next part of the thesis discuss the message scheduling in opportunistic networks. Opportunistic networks belong to the broad category of delay tolerant networks (DTN) that are based on the *store-carry-and-forward* routing principle [30], where a node stores a message into its buffer, waits until it moves into the communication range of some other nodes and then replicates the message. These networks provide limited or intermittent connectivity unlike mobile ad-hoc networks(MANETs). MANETs need to establish end-to-end communication links for the message transfer. On the other hand opportunistic network rely on opportunistic links established between the mobile nodes. Opportunistic networks support the applications that can tolerate delays.

Some of the examples applications of the opportunistic networking principle are:

- Underwater networks [22] Opportunistic networks in conjunction with sensor networks are being used to study the underground water levels. This information is then used for planning and management of the water resources.

- Space Communication[5] A very interesting application of the opportunistic network is the space communications or the Satellite Communications.

- Military networks [51] Opportunistic networks have found a major role in improving the battlefield communications and survivability

Opportunistic networks can have many applications in smart vehicular networks, social networking, agriculture and emergency networks.

The network environment in opportunistic networks is challenging due to the frequent disruptions because of the highly mobile nodes in the network. This node mobility is the reason for the intermittent connectivity between the nodes.

Efficient message delivery is one of the main problems that these networks have to face because of the intermittent connectivity. A number of protocols have been proposed to improve the efficiency of these networks in terms of average delivery probability and to minimize the average delivery delay. These protocol either propose an improved routing mechanism or more sophisticated message scheduling schemes. The routing protocols utilize a variety of methods to improve performance. For example:

- Probabilistic routing: [9], [45]
- Network coding: [57], [65]
- Controlled Packet Replication [59], [58]
- History-based learning [10], [38] of routes

Despite the efforts invested in designing improved routing schemes, one of the crucial factors that could potentially improve performance has not yet received much attention: the issue of message scheduling, in which a node, upon encountering one or more other nodes, makes a conscious decision about the sequence in which to replicate messages to those neighbours. There are only a few works that directly address message scheduling, for example the RAPID[6] protocol, GBSD protocol [38], and the Global History Based Prediction scheme [17].

An important aspect that has been overlooked in the research is the "contact time duration", i.e. the time during which two nodes remain in each other's range. Although there are some studies that mention *inter-contact time* (i.e. the time between the successive meeting of nodes[43]). However, to the best of our knowledge there has been only one protocol (called Opportunistic DTN Routing with Window-aware Adaptive Replication (ORWAR) [55]) that involves the contact time based localized message scheduling and drop policy but does not explicitly consider the presence of several neighbours at once.

This thesis presents a message scheduling scheme which, similarly to ORWAR, which incorporates knowledge of the remaining contact time (RCT) left between the nodes. Furthermore, its scheduling algorithm explicitly addresses the case of having multiple neighbours at once, and the scheduling algorithm makes decisions that take into account both the "quality" of the neighbours (measuring how close they could bring a message to its destination) and the remaining contact time to them. This scheme is called **Opportunistic Networks Routing with REmaining Contact Time (ONRECT)**. The term "remaining contact time" refers to the (estimated) time that remains until the contact is finished, i.e. the nodes move out of radio range. The main aim of this work is to assess the performance impact of ONRECTs' scheduling algorithm and to compare it against ORWAR with respect to the average delivery probability, the network overhead and the average delivery delay. Furthermore, as both algorithms use predictions of the remaining contact time, we compare the impact of ORWAR's estimator and the "ground truth" on their performance.

1.3 Problem Statement

1.3.1 Passive discovery scheme in IEEE 802.15.4 based WBSN

In many BSN applications there arises the need to discover other networks. An example is in applications where a BSN is attached to the body of a person. The sensor nodes collects data from different functions of the body. Depending upon the condition of the person, it is quite possible that this data needs to be transferred to the medical facility as soon as possible which means that this data has to be offloaded to a fixed gateway (e.g. installed at a persons home) which forwards the data towards databases and service centres for further processing. To offload this data, the BSN has to discover the destination network first.

Discovery is the process of learning the communication parameters of the destination network (e.g. its beacon order, frequency channel and duty cycle), followed by successful reception or exchange of packets [66] once searching BSN is in its vicinity. An early discovery of the destination network means the critical data could be transferred to the medical facility as soon as possible.

We consider a simple scenario in which a BSN is searching for a specific IEEE 802.15.4 network identified by the unique MAC address of its network coordinator. The searching BSN must connect to this specified network and no other, for example to leverage shared encryption keys to ensure privacy.

The IEEE 802.15.4 standard operates in 2.4 GHz ISM band. This band is sub-divided into 16 frequency channels. The coordinator of an IEEE 802.15.4

network selects one of these channels and operates permanently over it. The standard offers two different discovery strategies depending upon the mode in which the network is operating. In the un-beaconed mode only *active discovery* is possible where the searching device (listener) sends specific request packets on a chosen channel. If another network is operating in that channel, its coordinator responds to the request. Otherwise the listener switches to the next frequency channel and tries again. This process continues until all the channels are exhausted or discovery is successful. In the beaconed mode the only possible strategy is *passive discovery.* The listener listens on a particular channel for a specified time without sending any request. If it fails to receive a beacon, it switches to the next channel. This process continues until it hears the beacon or all channels have been tried. For passive discovery of beacons, one of the most important factors influencing discovery time is the listening process. This listening process defines when the listener should start listening, for how long it should listen on one channel, and which channels to visit. The issue of optimal passive discovery has been considered in the literature (see [66], [34]), but in the absence of any a-priori information about the frequency channel the search can take a rather long time on average.

1.3.2 Message Scheduling in Opportunistic Networks

Opportunistic networks are characterised by frequent disruptions, highly mobile nodes and no end-to-end connectivity in the network. For the transfer of a message from source node to destination node, the source node has to keep the message in the buffer until it connects with another (relay) node in the network. That relay node then waits for another intermittent connection with another node in the network to forward the message. To make this delivery successful, the source node might transmit multiple copies/replicas of the same message to the multiple nodes in the network upon contact. In this way a large number of message replicas are diffused in the network which makes the delivery successful in a short time but it exhausts the network resources.

Many solutions have been proposed to improve the delivery probability. However an important factor i.e. remaining contact time has not been much under lime light. The scheduling scheme ONRECT, proposed in this thesis utilise this factor to improve the delivery probability while consuming less network resources in terms of number of message replicas.

The ONRECT algorithm, transmits only a specific number of message replicas in the network. Each message is assigned a priority upon generation for scheduling purposes. These messages are queued in the buffer according to the priority. Upon contact with other node, the ONRECT algorithm chose which message to transmit considering many factors i.e. priority, destination of the node and the message and the choice of the best neighbour to send the message to.

1.4 Proposed Solution

1.4.1 Rumour-based Scheme: A new Passive discovery scheme

In this work, we present a new scheme to improve the time BSNs require to discover the destination network. We name this scheme as *rumour-based scheme*. This scheme is based on the simple *sweep* strategies introduced in

[66] (which we use as a baseline scheme) and adds an additional mechanism. The idea is briefly explained by an example. We consider a simple scenario, in which there are several mobile BSNs and a few fixed IEEE 802.15.4 networks, and a particular mobile BSN (the *searching BSN* or the *listener*) is searching for a particular fixed IEEE 802.15.4 network, referred to as FPAN. The mobile BSNs are moving around randomly according to a predefined mobility model. The key twist of the rumour-based scheme is that all mobile BSNs maintain a log of BSNs they have recently discovered, including their operating frequencies. This log includes the information about the fixed PANs that BSN has directly or indirectly heard from. This log is included in all beacon frames that are transmitted and which other BSNs use for discovery. This way the information about a particular BSN can diffuse among the mobile BSNs, helping the searching BSN to look on the right frequency.

Performance Measures

The main performance measure considered for this section, is the average discovery time which is the average time required to discover the destination network. The performance of proposed rumour-based strategy will be evaluated in terms of average discovery time and its performance will be compared with sweep strategies. The effects of some other parameters like the size of the playground, beacon order of the FPANS, speed of the mobile BSNs on the performance of our scheme will also be evaluated.

Hypothesis

We evaluate the following hypothesis:

- If the information about the destination network is diffused among the other BSNs, the average network discovery time can be improved. With the increase in the number of BSNs presents in the specified area, the information will reach the searching BSN more quickly which will reduce the destination network discovery time.

- The average discovery probability dependant upon a number of factors like the speed of the mobile BSNs, the beacon order, size of playground.

1.4.2 ONRECT: Message Scheduler for Opportunistic Networks

In this work, we present a new message schedule scheme for opportunistic networks. The ONRECT message scheduler considers a simple, yet very large set up as compared to the other studies mentioned in the 4.1 and uses a mobility model geared towards modelling of mobile entities in an urban setting. It includes both mobile nodes and stationary nodes. ONRECT uses controlled packet replication called Binary Spray and Wait [59] to control the number of message replicas for each message.

The messages are stored according to priority. When another node comes in contact with one or more than one nodes, it finds out which node is the best choice to transfer the message. This choice of best neighbour depends upon the destination of the node and the message. Because of this intelligent choice of the next hop neighbour, the messages are diffused in the direction of their destination. This improves the chances of the successful delivery of the message.

This thesis compares the performance of ONRECT with ORWAR. The ONRECT and ORWAR schemes are also compared against another baseline scheme, the Spray-and-Wait [59].

The results indicate that ONRECT can, in the presence of perfect remaining contact time information, outperform the other schemes for important performance indicators. At the same time, however, ONRECT shows a higher sensitivity to the quality of the available RCT information.

Performance Measures

The main performance measures are:

- **Average delivery probability:** It is defined as the percentage of generated messages which are successfully received by their destination within the simulation time

- **Effort required:** The effort required is in term of the number of messages replicas (of a single message) i.e. how many number of message replicas are required for successful delivery of a message.

- **Average delivery delay:** is defined as the time is seconds required for a message from its generation until first reception at the destination.

Hypothesis

The main hypothesis is:

- The knowledge of remaining contact time when incorporated with message scheduling can substantially improve the delivery probability, reduce the delivery delay and requires less effort in terms of number of message replicas.

- The choice of best neighbour greatly impact the performance of the ONRECT scheduling scheme

1.5 Contributions

The research presented in this led to the three contributions.

1. Investigations on the Passive Discovery schemes for IEEE 802.15.4-based Mobile Body Sensor Network

2. Improving Passive Discovery for IEEE 802.15.4-based Mobile Body Sensor

3. ONRECT: Scheduling algorithm for Opportunistic Networks

Chapter II

Rumour-Based Discovery: Background, Related work and System Model

2.1 Background

2.1.1 IEEE 802.15.4

The first version of the IEEE 802.15.4 was released in 2003. Afterwards, many amendments have been made with the most recent in 2017[1]. IEEE 802.15.4 is very popular technology specifically designed for low cost, low power consumption and low data rate LR-WPANS. This standard only defines the specifications for lower layer i.e. physical and medium access layer (MAC) sub-layers of the networks.

The devices can assume three different roles in this standard: PAN Coordinator, Coordinator and node/device. The PAN coordinator initiates the network and then allows other devices to join the network. The PAN coordinator controls the network and can communicate with any other device in the network. The PAN coordinator assigns a 64-bit address to each device or a short address could be assigned during association process that is used for communication. The coordinator can communicate with any other device in the network and can perform device association. However, they cannot initiate the network. The node/device are capable of performing limited functionality. They can communicate with the coordinators and PAN coordinators.

This standard classify nodes into two different categories: Full Functional Devices (FFD) and Reduced Functional Devices (RFD). FFDs are implemented with a general communication model. They can communicate with other devices and relay messages. FFD are capable of working as a *PAN coordinator*, a *coordinator* or a device. As a PAN Coordinator,

RFDs are simpler devices than FFDs because they require fewer resources in terms of memory, processing and communication. An RFD is implemented with minimal memory capacity, processing and other communication resources. They can run very simple applications, for example a passive infrared sensor[27]. They can connect with a single FFD at a time.

A PAN network can be a single or multi-hop network depending upon topology of the network. Each network can have multiple coordinators but there is only a single PAN coordinator. IEEE 802.15.4 based PAN networks can operate in either *star* topology or *Peer to Peer* topology. In star topology, there is only one PAN coordinator which is a fully functionally device. The rest of the devices in star topology can be FFDs or RFDs. The PAN coordinator controls the network and can communicate with any other device in the network. However, the rest of the devices communicate only with the PAN coordinator and not vice versa. In this topology, the PAN coordinator is usually single hop away from the rest of the devices.

In the peer to peer topology, the FFD devices can communicate with any other device which is within in its range in the network. Most of the

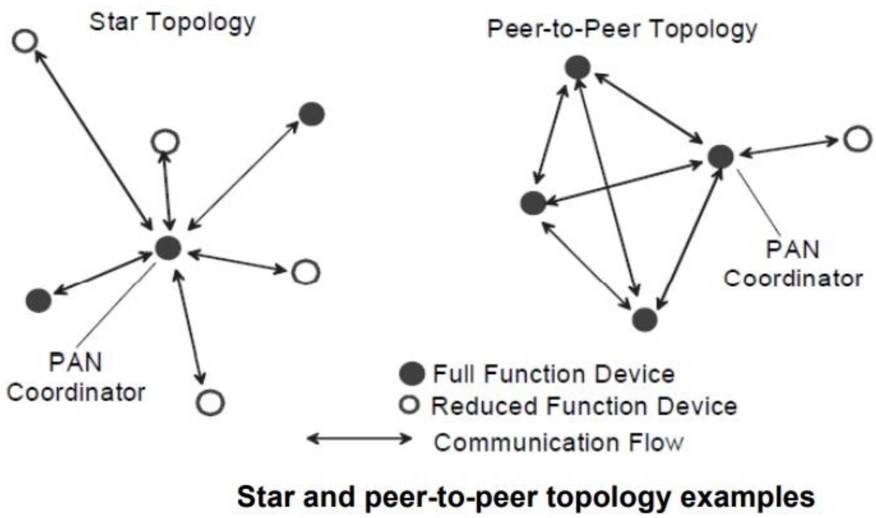


Figure 2.1: Network Topologies [27]

devices in this topology are FFDs but RFDs can also join the network as *Leaf Devices* at the end of the branch[27]. Because RFDs cannot connect with more than one device. The devices in the network can communicate to each other when they are in each others transmission range. The FFDs in the network can act as coordinators and can perform synchronisation among devices. However, each network can have only one PAN coordinator which is an FFD. The PAN coordinator transmits the beacons to the neighbouring devices. When the neighbouring devices receive the beacon, they can send request to the PAN coordinator to join the network. An example of such peer to peer PAN network is cluster tree network.

However, for this thesis we will consider star topology as BSNs have simple structure and they are connected to the PAN coordinator directly.

Physical Layer

The physical layer of this standard corresponds to the Physical layer of OSI model. This layer provides the functions of radio transceivers activation/deactivation, energy detection(ED), link quality indication (LQI), clear channel assessment (CCA) for channel selection and physical transmission/reception of the packets.

At the physical layer, IEEE 802.15.4 standard supports 27 frequency channels that operate in three frequency bands [27].
868.0 - 868.6 MHz: 1 channel is available in this band
902 928 MHz: ten channels available in this band
2400 2483.5 MHz 2.4 GHz Industrial, Scientific and Medical Radio Band (ISM) band

For this thesis, we will consider 2.4 GHz frequency band. This band is free and most widely accepted and used througout the world. This band offers 16 orthogonal channels. Each channel is 2 MHz wide while their centre frequecies are 5 MHz apart. Each of this channel supports bandwidth of 250 kbps. The frequency channels allocation are static as per the standard. Upon initiation, the BSNs can pick any of these channels and remain on this channel[27].

Medium Access (MAC) Layer

The MAC sub-layer offers two services MAC data service and the MAC management service. The MAC data service helps the transmission of MAC frames. The management service interfaces and manages the access to the physical layer. The MAC layer is responsible for the beacon transmission, synchronisation, channel access, GTS assignment, frame validation, acknowledged frame delivery, association, disassociation to the PAN coordinator, stat transitions (transmission, receiving and sleep) and limited security mechanisms.

The IEEE 802.15.4 standard based networks can operate in two modes: non-beacon-enabled and beacon-enabled mode. In the non-beacon-enabled mode, the nodes simply send their packets after a random back-off period to the PAN coordinator using the unslotted CSMA-CA mechanism. Before sending the packet, the nodes perform a carrier sense (CA) operation on the channel they are operating on. If the detected channel is busy then the node waits for a random back-off time and then sense the channel again. The PAN coordinator has to listen to the channel constantly for the up-link or the downlink request packets.

In beacon-enabled mode, the PAN coordinator sends beacon packets after specified period of time to maintain the synchronization. In this case, the nodes does not need to perform carrier sense. This mode is best suited for applications that require a high level of quality of services. In this mode time is sub-divided into consecutive superframes. A superframe is divided into active and inactive periods (compare Figure 2.2). A beacon is transmitted at the beginning of every super-frame. The beacon packet contain information about the PAN identification, super-frame structure and network configuration. It also has a payload field and it can carry a limited amount of data as well. The PAN coordinator use the beacon packets to synchronise the associated devices.

A superframe can be subdivided into active and inactive periods. The

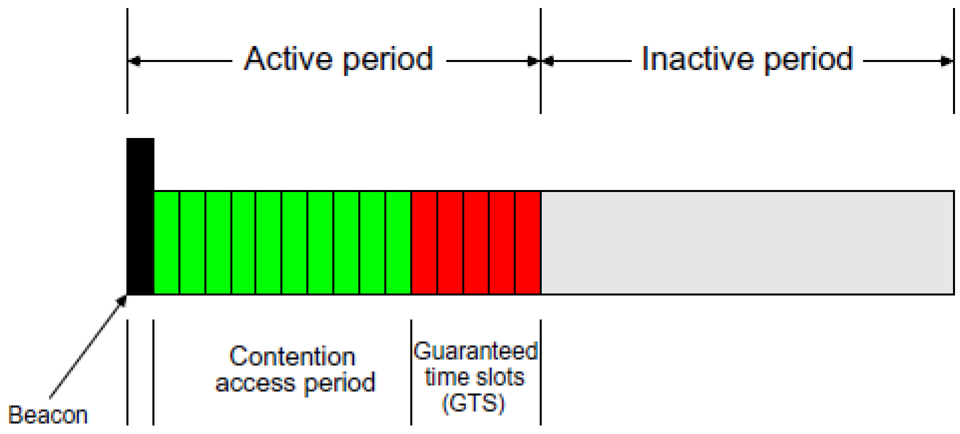


Figure 2.2: Superframe Structure

active period can be subdivided into 16 slots. These timeslots are divided into Contention Access Period (CAP) and an optional Contention Free Period (CFP).

The CAP begins immediately after the beacon. During CAP, the nodes contend with other devices to send uplink packets and request the packets from coordinator using slotted CSMA-CA or ALOHA mechanism. A device can send any kind of frame in this period except acknowledge frame or data frame which is sent in response to a data request frame. The transmitting device needs to complete its transmission during the slot or have to defer the transmission.

The CFP period immediately follows the CAP and is optional. CFP is subdivided into slots called *guaranteed time slots (GTS)*. The maximum number of the GTS could be seven. These slots are dynamically assigned by the PAN coordinator. A single sensor could be assigned more than one slot. However, The coordinator can dedicate maximum upto seven GTS to a node. The device transmitting in the GTS has to finish transmission during before the allocated slot finishes or the CFP ends in case of multiple slots are allocated to it.

For the applications that require specific bandwidth, the coordinator can assign the guaranteed time slots in CFP. The nodes can communicate with the coordinator during these slots without using any carrier sense. The inactive period follows the CFP. During the inactive period the coordinator enters in the low power or sleep mode.

In this work, the sensor nodes send uplink packets during the CAP period only using CSMA-CA.

The length of a superframe and active period are configurable. The superframe length corresponds to the Beacon Interval (BI) [27] given as

$$BI = aBaseSuperframeDuration * 2^{BO}$$

Where

$$aBaseSuperframeDuration = 15.36 \text{ ms}$$

And

$$\text{BO} \in \{0, 1, \ldots, 14\}$$

Therefore, the BI for the given set of BO:

$$BI = 15.36ms, 30.72ms, \ldots, 4.19m$$

It is very clear that when the BI increases with the increase in the BO. For the 2.4 GHz PHY. The length of the active period is given as

$$aBaseSuperframeDuration * 2^{SO}$$

where

$$SO \in \{0, 1, \ldots, 14\}$$

and

$$0 \leq SO \leq BO$$

The beginning of the active period is marked by a beacon frame which is transmitted in the slot 0. In beacon enabled mode, the nodes need to associate with a PAN coordinator before they can send/receive data packets to or from the coordinator. To associate with a coordinator, they need to receive a beacon packet from the corresponding coordinator. The beacon packet contain information about the communication parameters of the PAN coordinator. On receiving the beacon packet, the node then send an association request command to the coordinator. The coordinator then sends the acknowledgement of the request. At this stage, the requesting device is not associated with the coordinator. The coordinator, then checks if the sufficient resources are available for the association. If there are enough resources are available, the coordinator then generates the association response to grant the association. The requesting node is associated with the PAN and can communicate with the coordinator.

For this thesis, we will consider the beacon enabled mode.

2.1.2 Discovery Schemes

For an IEEE 802.15.4 based network to communicate with another network, it needs to perform the discovery process. Discovery of a network means to discover its communication parameters like frequency channel, duty cycle and Beacon order. But the discovery process is complete when the searching network hears at least one beacon from the intended destination network.

The IEEE 802.15.4 standard offers two different types of discovery schemes to search the infrastructure network based upon the mode the network is operating in. These strategies are active discovery and passive discovery.

In the un-beaconed mode only active discovery is possible. In this mode, the searching device has to initiate the discovery process. The device (listening node or listener) sends a beacon request packet on the particular frequency channel it is operating to discover the presence of a network. If there is a network which is operating on that particular frequency channel then its coordinator responds to the request. The listener waits for a response for a specified period of time. If there is no network operating on that channel so, there will be no response then the searching node will switch to the next channel and repeat the same process until it finds a network on any one of the channels.

In the beacon-enabled mode only passive discovery is possible. Two different types of passive discovery scans are offered by the standard: i) energy detection scan and ii) passive scan. In the energy detection scan, the coordinator obtains the maximum detected energy for the requested channel without gaining any information about the body producing the energy. In this mode, the coordinator, transmits a beacon periodically after a certain interval of time. The listening device is not allowed to send any request packet but it has to listens for beacons from coordinator. If the listening device receive a packet from the coordinator, it will know the communication parameters of the coordinator. The listener scans a particular channel for a specified duration. If no beacon is received during that time, the listener scans the next channel. This process continues until all the channels are exhausted.

The standard does not provide detailed information for passive discovery of network. For example, it does not mention in what sequence the channels must be scanned for the discovery. It also does not provide any information about the listening/scanning schedule i.e for how long the node should listen to a particular channel before switching to the next channel. The duration for the scanning is same for all the channels or the node is to spend different amount of time on different channels.

The important factor for the timely discovery of the network is the listening schedule, which specifies on which frequency channel the listener listens for how much time.

Sweep Strategies

For the reliable discovery of the FPAN within a short time frame, different passive discovery schemes have been proposed in [66], [34] and [36]. We will use the sweep strategies proposed in [66] as the baseline scheme, which uses the scanning mechanism offered by the IEEE 802.15.4 standard. They are illustrated in Figure 2.3 [66].

Sweep strategies identifies a simple listening schedule. In this strategy the listener operates in a time-slotted manner, with one timeslot corresponding to a beacon order of $Bo = 0$, i.e. $aBaseSuperframeDuration$ seconds. The basic unit of sweep strategy is a sweep of a given sweep order s. For a sweep of order s the listener listens on each frequency channel starting from the

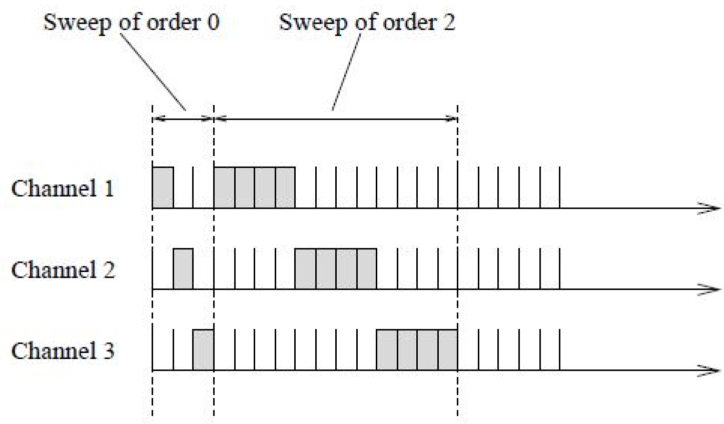


Figure 2.3: Sweep strategies

first channel. On each channel it listens for a duration of 2^s contiguous slots before moving to the next channel. The figure 2.3 illustrates the sweeps of order 0 and 2. The sweep strategy consists of k subsequent sweeps.

$$S = (s_1, s_2, ..., s_k)$$

where

$$s_1 > s_2 > ... > s_k$$

The listening process works as follows: For sweep order s_1 the listener starts scanning from channel one and subsequently scans for 2^s of slots on all the channels. In case of success, when the listener finds a beacon on any channel, the scanning process terminates immediately. In case, the listener does not finds a beacon on any channel, the listener tries the next sweep order s_2. This process continuous until either a beacon is found or all sweep orders $s \subset S$ has been exhausted. Some random waiting time 'w'is introduced between the subsequent sweeps. This waiting time serves to keep the beacon packets and sweeps out of phase. This process continues until either the desired network is found or all the channels are explored. In this work we will use a single sweep strategy that will comprise of a fixed number of slots to keep our scenario simple.

2.2 Literature Review

This chapter provides a literature review of the mobility models and the coordinator discovery schemes.

2.2.1 Random Way Point

As discussed in the previous chapters the Random way point (RWP) mobility model is stochastic model that describe the mobility patterns of a single entity like pedestrian or a vehicle. We have introduced two different versions of Random way point mobility model i.e. RWP Group mobility model and RWP with no Waiting time.

[31] This paper describes the design and performance of ad hoc network routing protocols using dynamic source routing among hosts for communication hence providing a decentralized network. Adhoc Networks do not rely on any infrastructure unlike other wired networks that either use distance vector or link state routing algorithms unlike them, source routing technique includes data packets sent by accessing the complete sequence of the nodes through which to forward the packet, sender then explicitly embeds the sequence list in the packet header based on the pre-embedded addresses. The packet hops to the receiver node through different nodes.

The protocol addressed is explicitly designed for wireless environments.

The paper provides the advantages of such protocol over other conventional protocols such as reduced bandwidth overhead and low power consumption by cutting the need for sending and receiving advertisement consistently over the network. Plus it adapts swiftly to the changes such as host movement. For performance evaluation of dynamic source routing protocol a packet-level simulator was constructed. Assumptions made for design and simulations of such a network includes full participation from hosts in an adhoc network, smaller diameter of the network having free movement of hosts with moderate speed as compared to packet transmission latency, wireless transmission range limitation and hosts ability to enable promiscuous receive mode on wireless network interface hardware. 20 simulations were conducted with varying movement rates and number of nodes. The paper purposes that results obtained after simulations were close to optimal. For simulations that involve the highest rates of host movement simulated, the overhead of the protocol is quite low, falling to just 1 percent of total transmitted data. Major limitation of the simulation was that the simulated environment was devoid of any obstacle. The paper also provides an optimized solution to the errors caused in adhoc network when two hosts wishing to communicate are not in the transmission range and there are not enough nodes between them. The solution proposed is catching the negative information in hosts route cache. Currently simulations are advancing towards additional optimizations for that the quantification of performance can be measured. Though security concerns of the protocol remained un-addressed in the paper, authors are currently examining these issues in terms of privacy concerns. Finally, implementation of protocol has begun on notebook computers for use by students in an academic environment.

The work [8] discuss the node distribution in the wireless ad-hoc networks. It has been observed that the spatial distribution of nodes moving according to the RWP model is non-uniform. Although the initial node positioning is typically taken from a uniform random distribution, the mobility model changes this distribution during the simulation. This effect, known as border effect, occurs because nodes tend to cross the center of Q with a relatively high frequency. This non-uniformity in node distribution has some important practical consequences such as it reduces the applicability of existing analytical results concerning ad hoc network. Secondly, this non uniform distribution implies that the representatives of the huge amount of simulation results could be impaired. This article investigates in detail the RWP node distribution as a function of mobility parameters.

The paper considers generalized version of the RWP model i.e. a node may remain static during the entire simulation according to the given probability. Thus allowing only a fraction of nodes to move. Furthermore it is considered as a fact that nodes are initially distributed according to some arbitrary spatial position. Lastly we allow pause time to be different after each movement period.

The paper discusses one dimensional and two dimensional cases of spatial distribution and develops mathematical models for each case involving certain theorems.

Simulations based experiments were performed to evaluate how well the mathematical models are for the two-dimensional node distribution approximate the actual distribution. Simulations tool takes as input the mobility parameter of the RWP model. In the first series of experiments, we consider a scenario with mobile nodes only and zero pause time. The result of this experiment shows that the approximation that we made in the derivation of mobility function does not significantly affect the quality of the result. In a second experiment, we evaluate the rate of convergence of the node distribution to the asymptotic distribution. In the third experiment, we validate that the normalized mobility component of the distribution is actually independent of the choice of the velocity. In the fourth series of experiments, we study how well our equation of the complete node distribution fits the experimental data in two hybrid scenarios. Finally, we verify the quality of our equation for the generalized RWP model with non-uniform initial distribution and random pause times. For this purpose, we extended the simulator by allowing nodes to be initially distributed uniformly at random in a smaller subarea.

The theoretical results presented in the paper have significant practical relevance. It allows to improve the simulation methodology used in ad hoc networking research community. Secondly the results provide serves as a starting point for the analytic investigation of ad hoc network with RWP mobility. In the end, the derivation of mathematical functions for the RWP gives us inside how this model behaves and why it behaves in such manner.

As mentioned earlier, the RWP model suffers the inherent problem of nodes converging to a single point after the some initial simulation time.

Navidi et al.[49] presented a solution for this problem. This paper shows how to implement a steady-state mobility model generator (mobgen-ss) for the RWM model. Then describes through simulation results, how to construct more reliable simulations for mobile ad hoc networks with mobgenss. The code for mobgen-ss is available at http://toilers.mines.edu.

Mobile ad hoc networks are often studied through simulations, and their performance can depend heavily on the mobility model that governs the movement of the nodes. It is generally true that the probability distributions of both location and speed vary continuously over time, and converge to a steadystate distribution, known in the probability literature as the stationary distribution. Because the distributions of location and speed vary as a simulation progresses it causes the performance of network protocols to vary as well. This causes the network performance in early stages of simulations to differ substantially from the network performance latter in simulations. Multiple solutions have been proposed each having its own drawback. The paper specifically targets the Random Waypoint Mobility Model because it is the most used mobility model for ad hoc network simulations. Virtually all published simulation results that use the RWM model begin with the nodes placed uniformly in the simulation area.

The paper publishes many simulations results that compare mobile ad hoc network random routing protocols using random Waypoint mobility model. All of these published simulation results began the simulations with either all or about half of the nodes paused. The paper describes that the performance results are an artifact of how long a simulation executes. Convergence of the average speed can take more than 1000 seconds of simulation time if the minimum speed is low. The simulation results stress the importance of using mobgen-ss, especially when the minimum speed is small or when a non-zero pause time is used. Since mobgen-ss is easy to use, paper encourages the

MANET community to begin using it for all their future simulations.

2.2.2 Discovery Schemes

There are many different neighbour discovery schemes that have been proposed but the area of passive discovery of IEEE 802.15.4 based networks is not a much focused. There are only few works that directly address this issue.

The *Disco* neighbour discovery protocol is presented in [15]. This work proposed a solution for low power, asynchronous discovery. The real challenge in neighbour discovery comes when the two discovering nodes operate on low duty cycles to conserve energy while optimizing the process of the discovery. This protocol is an adaptation of an ancient Chinese Remainder Theorem [50]. This protocol focuses on the scheduling of the duty cycles. The radio schedules are designed such that their wake up times are multiples of the prime numbers. This ensure that the nodes in the network have deterministic wake up times. In this way, no global coordination or frame structure is required to determine the duty cycles of the radios. This protocol selects a pair of prime numbers such that the sum of their reciprocals is the desired duty cycle. The nodes then transmit beacons and listens the slots which are multiples of the prime numbers. Disco selects the primes numbers automatically to match with the required duty cycles and turns on radio at the multiples of the primes. Disco provides flexibility to the applications to decide their duty cycles independently and still have high probability for network discovery.

The *Quorum* protocol presented in [60]. In Quorum protocol the time is sub-divided into sequences of beacon intervals (BI) which are then grouped into sets of contagious slots of n_2 , where n is global parameter that depends upon duty cycle. The n_2 slots are arranged as an $n * n$ matrix. A node can pick any column and row in that matrix and scan the channel during the slot represented by the corresponding value. In this way, if the two nodes pick random row and column, that means they will have two slots when they both will be awake and can discover each other.

[32] presents *U-Connect* protocol for synchronous and asynchronous protocol. U-connect is low power transmit and low power listening protocol as compared to the Disco and Quorm. Similar to [15], this protocol is also based on the selection of prime numbers. This work evaluates the performance of Disco[15], [60] and *U-Connect* using a power- latency product metric. This metric is basically modelled from the fact that low duty cycles results in low energy utilisation which ultimately result in high latency and vice versa. There is always a trade off between latency and duty cycles. This *power-latency product metric* was derived to find the best trade off solution for neighbour discovery.

Just like *Disco*, U-Connect also allows the nodes to pick dissimilar duty cycles while keeping the energy consumption low to make the successful neighbour discovery. The listening schedule for nodes in this protocol is divided striclty into time slots. The listening schedule follows the duty cycles from Low Power Listening Scheme (LPL) [16]. In LPL scheme, the radio listens periodically for transmission. However, in U-connect there is an additional condition for the listening schedules. For this protocol, the period of listening have to be prime in number of slots. The results from the experiments prove that Disco and Quorm are 2-approximation protocols while U-connect is 1.5-approximation protocol.

However, all of these above mentioned protocols are not IEEE 802.15.4 specific. There is only a few research works available that specifically discuss the problem of coordinator discover in IEEE 802.5.4. The work mentioned below address the issue of neighbour discovery in IEEE 802.14.5 based networks.

The dual beacon scheme presented in [36] makes use of two different types of beacons, namely Long Range beacons (LR-Beacons) and Short Range beacons (SR-Beacons), to discover the network. These beacons are emitted with different transmission range in an interleaved manner during the same Beacon Interval. The LR-Beacon serves the purpose of announcing the sensor nodes in the area about the presence of the network. While the SR-Beacon actually inform the sensor nodes that the actual data exchange can take place.

Bashir, F. at el. presented a new strategy of passive discovery called 'CAPD' in [7]. CAPD tries to reduce the Beacon Interval of the coordinators near to the mobile end node. The coordinator keeps the 64 bit MAC address of the associated nodes in a table. The coordinator of the end nodes use the Link Quality Indicator (LQI) to speculate the mobility of the nodes. CAPD protocol adds three fields in this table to precisely detect the node mobility. All these three fields keep record of the three different LQI values related to the associated node. If the algo detects that any node is moving away from the coordinator in a specified time interval, the coordinator issues a broadcast *decrease beacon interval (DBI)* message to the neighbouring coordinators. However, this algorithm is triggered only when a coordinator receives packet from a associated node. The receiving (neighbouring) coordinator can decrease the beacon interval immediately after receiving the DBI or can wait until the current Beacon interval finishes. If it decides to reduce the beacon interval immediately, then the associated nodes might lose the synchronisation.

Karowski, N. at el. investigated the discovery of IEEE 802.15.4 based static and mobile networks in [34]. This work presents two new optimized asynchronous and multi-channel discovery schemes namely OPT and $SWOPT$ and a 'Sub-Optimal algorithm (SUBOPT)'. These strategies make use of the idea of aggressive channel switching after some specified interval of time to optimize the discovery of nodes with smaller beacon orders. *Optimized (OPT)* strategy scans a channel for one time slot that corresponds to $BO = 1$. This leads to high number of channel switching. While the *SWitched Optimal ($SWOPT$)* strategy, scans the channel for number of slots corresponding to a minimum Beacon order of a considered set of Beacon orders. This number of channel switches in this case are less as compared to OPT. However, both of these proposed strategies are complex and require a lot of computational power. As compared to these strategies, the *SUBOPTimal* strategy, is less complex and requires less memory.

2.3 System Model

This section describes system model and explains the important components of the model.

2.3.1 *Methodology and Tools*

Simulation methodology is adopted when conducting experiments on a real time test bed would be either impossible because of the cost of equipment or impractical because of the complexity of the algorithm or the scenario is difficult to generate in the real time scenario. Simulation provides a cheap alternative to perform the experiments in a controlled environment and test new ideas while keeping the cost low.

For this work, the simulation methodology was adopted to conduct the experiments. Thorough research was conducted to find a suitable candidate simulator. The features that were looked into while making the choice of right simulator were: i) A basic implementation of the IEEE 802.15.4 protocol, ii) physical layer implementation of the radio module and frequency channels, iii) MAC layer implementation to test the our enhanced features of beacon frames and node association process, and iv) open source simulator.

There were many suitable simulation software optionw available on the market. OPNET [47] provides all the features for this work. However, OPNET is a commercial software and it requires license. The other alternatives are NS2 [46] and OMNET [61]. NS2 provides implementation for Wifi and Wimax, however, there is no built-in module for IEEE 802.15.4. Similarly, OMNET, itself does not have any built-in module for IEEE 802.15.4, but there are many libraries that operate as an addition layer on top of OMNET with built in implementation of the basic functions of PHY and MAC layer of this standard. Examples are MiXiM [4], INET Framework [3], and Castalia [2].

These simulators (and libraries) were carefully compared for the features required for the implementation of this thesis and Castalia was chosen. The reason behind this choice was that Castalia is an open source simulator that is specifically designed for wireless sensor and body area networks. Castalia provides a full implementation for IEEE 802.15.4 standard which is the main requirement for this thesis.

However, there are drawbacks of this simulator. i) One of the main issue as far as this is concerned was the absence of a proper mobility model. When the experiments for this work were conducted there, Castalia supported only straight line mobility. ii) The other draw back was the absence of a node association/dis-association process

However, since Castalia is open source simulator, therefore, it was feasible to incorporate custom built modules into it. For this thesis, mobility module was extended and a node association process were added into the simulator. There were two mobility models i) Random way point and ii) Random Walk were added in the mobility module to carry out the experiments.

2.3.2 Channel Model

The radio channel model considered in this work is the standard *log-distance model* [52]. The path loss for this model is given by

$$PL = PL_0 + 10\gamma \log_{10}(d/d_0)$$

where PL_0 is the path loss at reference distance d_0 (which we assume to be 1 m), d is the length of the path and γ is the path loss exponent. According to the work [54] [18], when sensor nodes are very close to the body the path loss exponent assumes very high values around 7.5 (due to diffraction around the body). For this work, the path loss exponent is chosen as $\gamma = 2$, since this thesis is mainly concerns with the situations where the listener receives (through unobstructed space) beacons from a foreign network, the FPAN. The transmit power of $-15dBm$ is chosen for all sensor nodes.

2.3.3 Body Sensor Network (BSN) Model

A typical BSN in this thesis consists of a coordinator and a maximum of two associated node. In most of the experiments, there is only one associated node. In order to study the effects of the number of associated nodes on the discover probability for certain certain experiments, however, the number of associated nodes is increased to two. The associated nodes are connected to the coordinator in a star topology in beacon enabled mode.

The associations process is a three way process:

Step I : The coordinator in this case periodically transmits beacons at regular intervals. The node willing to associate with the coordinator use sweep strategy to listen for a beacon on all the frequency channels. When this node receives the beacon on any channel, it switches to that frequency channel and then sends an association request to the coordinator. If the coordinator already has one associated node, the coordinator responds with a negative acknowledgement and the process terminates here. The concerned node then looks for another coordinator.

Step II : If the intended coordinator does not have any associated node, it accepts the request and replies to that association request.

STEP III: The associated node then send an an acknowledgement to the coordinator. At this point, the node is now associated with the coordinator.

The coordinator and the associated nodes maintain the synchronisation via the beacon messages transmitted by the coordinator. The coordinator itself, initially pick up a frequency channel and remains on the same channel. The coordinator in this case designates the listening strategies to the associated node. Once a node is associated with it, the associated node then starts sweeping the channels to hear beacons from other coordinators. The associated node in the BSNs use the sweep strategies to scan the frequency channels. That means the node is switching the frequency channels to listen for the beacon packets. While the associated node sweeps the channel, it dis-associate itself from the coordinator. After it completes a sweep, it re-associates itself again with the coordinator. When the associated node re-associates itself with the coordinator, it sends its exchanges the information with its coordinator. This information consists of the communication parameters of any other coordinator, from which the associated node has received a beacon during sweep.

2.3.4 Mobility Model

For the performance evaluation of a protocol on a simulation test bed it is necessary that the experiments are conducted under realistic conditions. Mobility is one such condition and an integral part of the BSNs. As the BSNs consist of nodes mounted to a human body that means the position of the nodes change with the movement of the person. To re-produce the movements of the body, a realistic mobility model is an important requirement for this thesis. There are two possible ways the mobility can be simulated in a network i.e. traces and synthetic mobility model.

Traces are the mobility patterns that have been observed in the real time by collecting the logs of the connectivities among three moving devices from deployment of the devices[12]. There exist large repositories of the traces that are available ti use. For instance, at Dartmouth College, studies have been conducted for the WiFi traffic measurement[19]. There is another very famous repository for traces called CRAWDAD [37]. The traces available are not standardised cannot be used directly by the simulators.

While, the synthetic mobility models are the mathematical models that are specifically designed to capture the movement of the entities like nodes, person etc. Synthetic mobility models gained more popularity compared to traces because i) most of the traces repositories are not publicly available, ii) it is difficult to validate the data, and iii) for the research purposes, there might be a need for the underlying mathematical model of the movement which does not exist for the traces [31].

There are many synthetic mobility models proposed to meet the requirements of different types of movement like vehicle, individuals, group mobility models. Most commonly used mobility models generalise the movement of individual devices/person. Some of the most popular mobility models are Random Way-Point (RWP) and Random Walk (RW).

Random Way-Point Mobility Model

Random Way-Point is a simple stochastic mobility model which depends on parameters like the size of the area (playground), initial node distribution, their movements, destination, pause time, minimum and maximum velocity [53].

In RWP the initial node distribution is very important. However, the initial node distribution does not follow any realistic pattern. Typically, the nodes are initially randomly distributed in the playground. The nodes pick up a random point (way-point) [31] in any arbitrary direction in the given playground as destination and start moving towards that point with some velocity selected from a a given range of velocities. Once the node reaches that destination point, it takes a pause for a random amount of time, also selected from a range of random wait time 2.1. At that point, the node selects another random point as destination in the playground and starts moving. The next way-point could be in any direction as irrespective to the previous way-point.

The spatial distribution and speed of nodes changes significantly during the initial simulation time, which produces highly variable results. The probability to choose the next destination in the center of the area is higher. After some time, the nodes tend to cluster near the centre, the inter-node distance decreases and ultimately this convergence leads to unjustified performance improvements [12]. To resolve this issue. In this thesis, a variant of the RWP model have been used. In the work presented in [12], it was observed that after a duration of simulation time, the system starts to converge and the results thus produced are more consistent. It was observed that that duration approximates to about 1000 simulation seconds. After this duration, the network starts to converge and starts producing more reliable results.

Group Mobility Model

Synthetic mobility models like Random Way Point and Random Walk describe the movement patterns for a single entity like a node or a pedestrian etc. However, there come scenarios when a group of entities move together. Their mobility co-relates to each other. For example, in case of Body Sensor Networks, a group of nodes is attached to the body of the person. When a person moves around, the group of nodes moves as a whole. In such scenarios, the RWP and RW are not sufficient as the nodes in these models move independent to each other and their is no co-relation in their mobility.

Group mobility models were proposed to meet the requirements of such scenarios. The most common model is The Reference Point Group Mobility (RPGM) Model [21]. RPGM is primarily based on RWP mobility model, however, in this case, each node has two movement components i.e. individual and group 4.2.

In this thesis, we customised the the Random way point mobility model for BSNs to suit the requirements of experimental scenario. Since the BSNs consists of a coordinator and an associated node. And these nodes are attached at different positions on the body of a person, therefore when the person moves, the position of the nodes change and the relative distance from each other also changes. That means, at some point, they are closer to each other and at other instants their mutual distance increases. In order to mimic this behaviour, the coordinator is set to pick up the way point from the playground. It then starts moving towards the selected way point. The associated node selects its position within < 1 meter's distance from the position of the coordinator at a given instant. In this way, the associated node remains close to the coordinator but their mutual distance varies.

A middle-aged person can walk with an average speed of around 1.8 to 3 km/h. Hence, it is assumed that the minimum and maximum velocity for the nodes would be between 0.5 m/s to 2 m/s. The mobile BSN selects a speed from a uniform distribution between minimum and maximum speed. When it reaches its destination it pauses for 5 seconds and starts over. However, an important point to mention here is that the RWP model employed here comes with the inherent problem of nodes concentrating in the centre. For this purpose, in the experiments some of the initial simulation time (the first 1000 seconds) until the network converges were discarded. Only after this time the searching BSNs starts its search for the destination FPAN, and the discovery time is measured from this point of time onwards.

2.3.5 Network Setup

In this experimental set up there are two types of networks, mobile BSNs and the stationary BSNs. The deployment comprises of n networks, including the mobile BSNs and the BSNs. Each BSN consists of a coordinator and an associated node. Each network (fixed or mobile) picks its frequency channel randomly from the 16 channels available (using a uniform distribution), and remains on that frequency throughout. The coordinators transmit a beacon after each beacon interval.

Each network draws its beacon order randomly and independently from $\{3, 4, 5\}$ according to a uniform distribution. This window was chosen for beacon orders to keep simulation times tractable and to focus on the impact of knowing the right frequency by ensuring that nodes knowing the right frequency will find their target coordinator with high probability when they are close enough. Each node in this model is equipped with a single CC2420 omni-directional transceiver. Each BSN is identified with a unique MAC address.

There are two particular networks: one mobile BSN (also called the searcher) and one fixed network (called the FPAN). The main aim is the time the searcher needs to find the destination FPAN. It is assumed that the address of the FPAN coordinator is already known to the listener / searcher.

In this thesis, we assume an unbounded targeted discovery, i.e. the searcher does not put a bound on the allowable time for discovery. However, there is a limit on simulation times (see below). For simplicity, it is assumed that the searching BSN is capable of listening continuously without interrupting its other vital functions. To achieve this, the coordinator delegates the listening responsibility to one or more associated node(s). The listener uses a sweep strategy with $S = \{10\}$, which makes it very likely that the searcher will find the FPAN when it is on the right channel and close enough to the FPAN.

The experiments were conducted with a sweep of order $S = \{10\}$ and the beacons orders $\{3, 4, 5\}$. The beacon orders were kept smaller to keep the beacon interval small which mean that after a small interval of time a beacon packet will be transmitted by the coordinator and that would increase chances of the network being discovered.

The BSNs in this system model transmit only the beacon packets and no data packets. This allows a better focus on discovery-related aspects.

Parameter	**Numerical Values**
Sweep order(s)	10
Min. Speed	0.5 m/sec
Max. Speed	2 m/sec
Transmit Power	-15 dBm
γ	2

Table 2.1: Parameters vs Values

Chapter III

Rumour-Based Discovery: Algorithm and Performance Analysis

IEEE 802.15.4 standard provides limited support for passive discovery of the network. For example, the standard does not support the delegation of the discovery tasks to the other nodes which might be coordinated with any associated node in the network. In this case, the PAN coordinator that wants to transfer a message to another network must constantly listen the channel. During this time, the coordinator is unable to provide other services to its own network. In addition to this, for a quick and optimal discovery of the foreign network, one of the important factor is the listening schedule. The standard does not provide any information of the listening schedules a coordinator needs to follow to discover the destination network.

The proposed passive discovery schemes "sweep strategies" presented in [66], [34] address the above-mentioned issues in the standard. It offers a listening schedule and mechanism for scanning the channels in order. Sweep strategies are optimal within their class, however, sweep strategies tend to require a relatively large amount of time for network discovery due to the risk of looking at the wrong channel. This problem is exacerbated in the presence of mobility. The reason is the intermittent connectivity between the listener and the targeted FPAN. For example, it is quite possible that while the discovering BSN is scanning the destination channel where the destination BSN is operating, they both move away from each other and are thus out of the transmission range.

In the light of the above mentioned issues, there was a need for a discovery scheme that could discover the destination network optimally while addressing the underlying issues. In this thesis, we propose a new passive discovery scheme called "rumour-based discovery" that takes a different approach to discover the destination network.

3.1 Rumour-Based Scheme

As the name suggests, the idea behind the rumour-based scheme is to spread the rumours about the communication parameters of the destination network. The main goal of rumour-based discovery is to reduce the discovery time of the targeted FPAN. As mentioned earlier that the listening schedule is a very important factor for the optimal discovery of the targeted FPAN. Rumour-based scheme utilises a simple sweep strategy (which is also used as baseline scheme in this thesis) as the listening schedule. This scheme augments the sweep strategies with an additional layer of logic.

Rumour-based schemes take advantage of the fact that the beacon frame can not only carry the information about the communication parameters of the source network but they are also capable of transporting a small amount of data as part of the payload. This data payload is then used to carry information that is useful for the discovery of the target FPAN. The data carried by the beacon payload is basically the information about the communication parameters of the other networks (that might include the destination network). In this way, the information about the communication parameters of the destination network is diffused throughout the network which makes it easy for the searching BSN to discover the communication parameters of the networks.

Another important point to mention here is the designation of the listening to another node in the network. The coordinator of the searching BSN designates the listening responsibility to one of the associated nodes which constantly listens to the channels as per the selected sweep strategy.

For the rumour-based scheme, the process of discovery is comprised of two steps.

- To discover the communication parameters of the destination network

- To hear a beacon directly from the destination coordinator

This happens when the searching BSN hears about the communication parameters of the destination from another network. However, in some cases, both of these steps happen at once when the searching coordinator hears a beacon directly from the destination coordinator.

In this scheme, the searching BSN learns information about the communication parameters (especially the frequency channel) of the FPAN by two different means:

- If the own listener node hears a beacon from the FPAN, or

- it receives this information from a third party WBSN's beacon packet.

Once the node designated for listening (of the searching BSN), receives this information, the searching node would switch to the target frequency channel and continue listening until it receives a beacon from the target FPAN.

Every BSN coordinator in the network maintains a small database in its memory. The data stored in this database is related to the networks, the coordinator has heard about either directly or indirectly from a third party WBSN's beacon. This database is maintained by coordinators of both fixed and mobile networks. This thesis refers to this database as "PAN-DB".

The PAN-DB includes only a single table that has four columns, namely: MAC address, frequency channel, beacon order and the time elapsed. It is important to mention that the PAN-DB stores the information about fixed networks only. This thesis makes the simplistic assumption that the fixed PANs are aware of themselves being fixed by a mechanism outside the scope of this work. The information in the local PAN-DB is diffused throughout the network using the beacon messages.

When a coordinator sends a beacon it includes all entries from its own PAN-DB into the payload of the beacon. The resulting beacon frame structure is shown in Figure 3.1. The reason that the size of the PAN-DB small because it corresponds with the data field of the payload of the beacon. That's the reason, PAN-DB accommodates only six entries for the FPANs that it has heard of most recently.

The restriction to six entries is imposed due to the following reason. The maximum size of a beacon message is 127 bytes. Whereas the data payload of the beacon varies between 75 -107 bytes. One entry in the PAN-DB takes about 11 bytes. This includes:

- 8 Bytes for the Mac address (64 bits)
- 1 Byte for the frequency channel
- 1 Byte for Beacon order
- 1 Byte for the Time elapsed field

The contents of the PAN-DB are transmitted in the same format as part of the beacon. However, the size of each record could be shortened by 1 byte, if the frequency channel and beacon order are both stored in 1 byte. The time field counts the elapsed time in seconds.

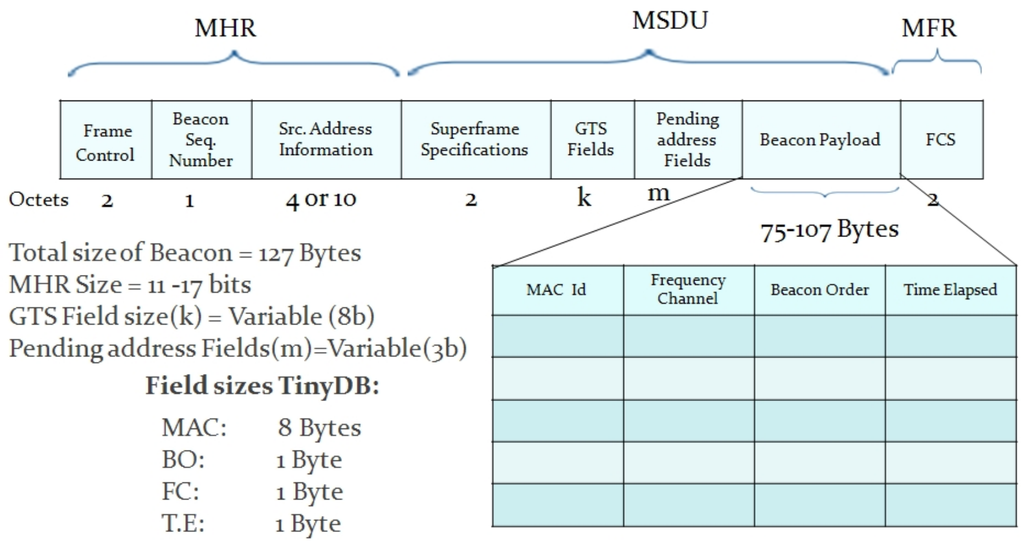


Figure 3.1: Beacon frame structure

3.1.1 How it works

The listener operates according to the sweep scheme discussed earlier in the network set up 2.3.5. It starts scanning channel one at t=0. The listener scans this channel for a sweep of order 10. When it does not hear any beacon on this channel it starts listening on channel 2 and this process continues until it hears a beacon on any one of the channels. The listener listens continuously according to the sweep method with a sweep order of 10. When all channels have been visited and the listener does not hear any beacon on any channel, it starts over the search again from channel one. If a beacon is discovered during this process on any channel, it scans through the PAN-DB entries listed in the beacon payload. For example, when the coordinator A hears a beacon from coordinator B, then:

- If B itself is a fixed network, then its parameters will be added to the database. If B is a mobile network then A will look into B's PAN-DB carried in the beacon.

- If B lists an FPAN X which the coordinator A has not yet heard about (i.e. it does not have an entry for X in its local PAN-DB), it will add an entry of X in its database if there is still room left. If there is no room left but X has a elapsed time field that is more recent than the oldest entry in A's local PAN-DB, then the oldest entry is replaced with the entry for X.

- Otherwise, if A already has an entry for X in its database, then A checks its elapsed time field.

- If the elapsed time field for X in B's beacon is more recent than the elapsed time field for X in A's database, then A updates the elapsed time field in its database with the elapsed time value found in B's beacon payload.
- Otherwise the entry remains unchanged.

In addition to this per-beacon processing the coordinator A is required to update the elapsed-time fields of all existing entries in its PAN-DB as time passes. If the searching BSN A hears the information about the target FPAN from a third party's beacon, it switches to the destination frequency channel and starts listening for a beacon from the FPAN. In this particular case the information about the target FPAN is never removed from the PAN-DB.

It is important to mention that, target discovery is only considered to be successful when the searching BSN hears a beacon directly from the destination network.

3.1.2 Performance Measures

The overall performance gains of rumour-based scheme depends upon many factors like the size of playground, Beacon Interval, the sweep strategy and the number of mobile nodes in the network.

1. Discovery Time

   Our main performance measure is the discovery time. If it is assumed that there is only one FPAN in the network then the primary performance measure is the average discovery time. The discovery time can be defined as:

$$T_d = T_s + T_h$$

where T_d = the total time required to discover the network

T_h = the time duration from the beginning of the search until it hears about the communication parameters of the FPAN (either directly or through other mobile BSNs beacons)

and T_s = the time duration from the time where the searching BSN switches to the target frequency until it hears a beacon from the FPAN.

2. Discovery probability The other performance measure of interest is the discovery probability. This is the probability that the BSN successfully discovers the FPAN during a fixed time budget in a specific area size. With a higher number of mobile nodes, the information spreads quickly throughout the network and in return improves the discovery probability.

Main Control Knobs

Following are control knobs that have a direct impact on the performance of the rumour-based scheme.

1. Impact of Beacon Order

   Another important performance measure is the impact of beacon order on the discovery probability and the discovery time. If the beacon order is large it means that the beacons are emitted after a longer interval of time which in return means that the small number of beacons are emitted in s specified amount of time. The small of beacons means it will take the searching BSN more time to scan the channels and the process of delivery will be delayed.

2. Impact of number of associated nodes

   In rumour-based scheme, the coordinator designates the listening responsibility to an associated node. If there are more number of nodes that are listening on different channels, there is more possibility that the target network will be discovered fairly early.

3. Impact of Speed

   The effects of increasing the speed on discovery probability and discovery time are different in different playground sizes. For small sized playground, more speed means, the BSNs can go in and out of each other's range in a small interval of time. Which means that the discovery time and discovery probability will be decreased. However, these effects will be reversed in the large playground area, where the nodes can come closer to each other due to high speed which makes it easier to discover the network.

3.2 Performance Analysis

In this chapter, the performance of rumour-based scheme is evaluated using simulation methodology.

Comprehensive simulations were performed to evaluate the performance of rumour-based scheme. Different sets of simulations were performed with different values of important parameters like playground size, speed and beacon order etc. The results of these simulations were validated against simple test cases.

The graphs presented in the chapter are generated after running each simulation for substantial number of times. Each point in the graphs represents an averaged measure of several replications. In each replication the initial positions and waiting times of the mobile BSNs are chosen randomly.

For each set of parameters a sufficient number of replications were carried out to obtain a relative confidence interval of 5% at a confidence level of 95% for the discovery time.

In order to present the results in a meaningful way, the results have been normalized. More specifically, the peak observed value in all of these experiments was considered as a base value for comparison. The other values are scaled as a percentage in comparison to the peak value.

3.2.1 Simulation Setup

rumour-based scheme is implemented in the Castalia network simulator, version 3.2 [2]. The maximum simulation time for each run is 18,000 simulated seconds (5 hours), at which point the simulation terminates. However, a simulation run might terminate earlier than this time. This happens if the searching BSN makes a successful discovery prior to the expiry of this time.

To analyse the performance of this scheme, this thesis considered varying playground sizes. The size of these playgrounds varies from minimum 100×100 m^2 up to maximum 400×400 m^2. In each of these different sized playgrounds, exactly one fixed network has been placed at a random position. This fixed network is the destination network (destination FPAN) the listener is searching for. The rest of the BSNs in the network are mobile. The number of mobile BSNs vary in the network. One node in each of these mobile BSNs is designated to listening only. One of these mobile is configured to be the listener i.e it is searching for the destination FPAN.

At the beginning of each simulation run the FPAN and mobile BSNs pick their frequency channel randomly and independently of each other from the 16 frequency channels offered by the standard. These FPANs and mobile BSNs also randomly pick up a beacon order from the range BO $\in \{3, 4, 5\}$. The mobile BSNs move around randomly in the playground according to the RWP mobility model. The listener listens on each channel according to the sweep scheme with an order of 10 slots.

During this movement, if it listener hears a beacon from the target FPAN on any channel, the simulation stops immediately. In this process of listening, the listener listens beacons from other BSNs. If it hears a beacon that has the information about destination network, it switches to the frequency of destination BSN and remains on that channel until it hears a beacon directly from the destination FPAN. In this case, the discovery time is noted. Otherwise, when the listener fails to hear from the FPAN i.e. destination FPAN is not discovered, no discovery time is recorded. In this case, the lack of FPAN connectivity is reflected in the discovery probability results.

3.3 Results

3.3.1 Average Discovery Time

The main focus of this work is to reduce the average time required for a successful discovery of the target FPAN. The experiments were conducted with four different playground sizes from 100×100 m^2, up to 400×400 m^2.

For each of these playground sizes the maximum average discovery time is obtained when there is only one mobile BSN in the network. Because there is a successful discovery only when the mobile BSN hears a beacon directly from the FPAN .In this case, rumour-based scheme behaves essentially as a sweep strategy.

In the graphs, the results were normalised for the cases with two or more mobile BSNs by dividing them by the time average time required for one mobile BSN. However, there it is important to mention that while computing the average time, only cases were considered when a successful discovery was made.

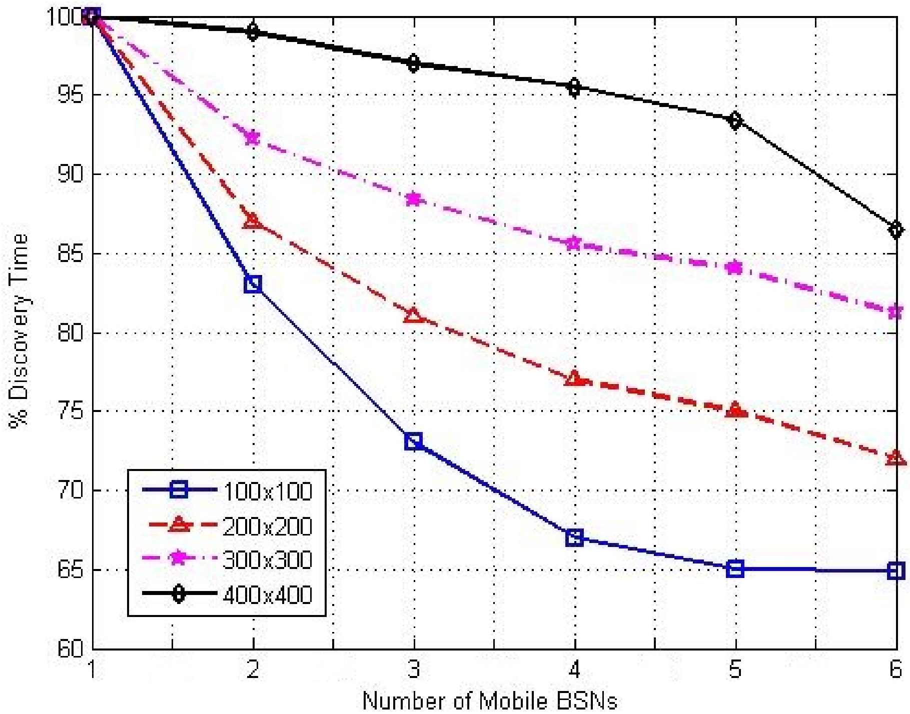


Figure 3.2: Discovery time

The results for the average discovery time for the different playground sizes are presented in Figure 3.2. In general, as the playground size increases, the BSNs are far from each other. It takes mobile BSNs more time to discover the destination FPAN and thus the probability time also increases. On the other hand, more number of mobile BSNs in the network means that there are more information carriers in the network. The information about FPAN is quickly available which reduces the time to discover the FPAN and improves the discovery time.

The following points are noteworthy from the Fig 3.2:

- With playground size 100×100 m^2 (the smallest area tested) the improvement in the discovery time is maximum. The discovery time is maximum when there is only one mobile BSN in the network. In this case, the listener has to hear the beacon directly from the FPAN. This time decreases quickly with each additional BSN in the network. The system starts to converge between the fourth and sixth BSN. There is insignificant drop in the discovery time with the addition of fourth until sixth BSN in the network. A total drop of 35% is obtained in average discovery time with six BSNs in the network.

- With an increase of area size to 200×200 m^2 and 300×300 m^2, a significant performance improvement was observed with increasing number of BSNs. The discovery time drops with the addition of each BSN. With six BSNs, a reduction obtained in the discovery time of 27% and 18% for area sizes of 200×200 m^2 and 300×300 m^2, respectively.

- When the playground size was 400×400 m^2, the maximum size tested in these experiments, the performance obtained with six BSNs still yielded a discovery time reduction of 14%.

However, for this playground size, it is worth noting that until the addition of the fifth BSN no significant reduction was observed. The most significant drop was observed with the addition of another BSN. A rapid drop of almost 10% was observed with this addition.

These results support our hypothesis that if the information about the destination network is spread in the network, the discovery process takes less time and there is considerable potential for saving time. These results also prove that larger the size of the network in terms of number of BSNs, the information about the destination will diffuse more quickly making it easier for the listener to discover.

3.3.2 Discovery Probability

Another important performance measure is the discovery probability. This probability is defined as the percentage of simulation replications (for a given set of parameters 2.1) in which the listening BSN really discovers beacons coming from the FPAN within the allocated five hours simulated time. The results for the rumour-based scheme are shown in Figure 3.3, in this figure the special case of having just one BSN also indicates the performance of the baseline scheme as in the absence of any other mobile BSN, the listener which is using sweep strategy has no choice but to hear directly from the destination FPAN.

In general, as the playground size increases, the BSNs are more sparsely placed. The chances to discover the destination FPAN decrease and thus the probability discovery also decreases. On the other hand, when number

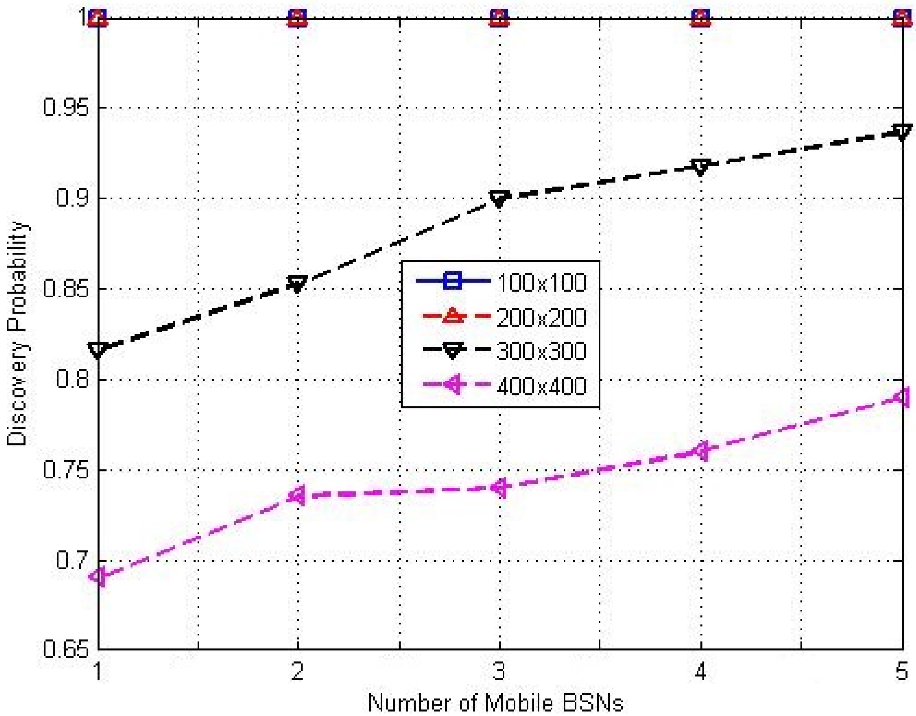


Figure 3.3: Discovery Probability

of mobile BSNs increase in the network, there are more chances that the information about FPAN spreads in the network which makes it easy to discover the FPAN and improves the discovery probability The following points are remarkable:

- The discovery probability decreases with increased area size, as can be expected.
- The discovery probability is very close to one for the smaller playground sizes of 100×100 m^2 and 200×200 m^2, regardless of the number of mobile BSNs.
- For the larger field sizes of 300 m^2 and 400×400 m^2 the discovery

probability increases with increasing number of BSNs. The smallest achieved probability was 0.82 for 300×300 m^2 and 0.69 for 400×400 m^2. With the addition of the fifth BSN the discovery probability improved to 0.94 for 300×300 m^2 and 0.79 for 400×400 m^2, respectively.

- Also worth noting is the improvement of 14% in the discovery probability when the area was 300×300 m^2 and the number of BSNs was increased from 1 to 5. Comparatively, the increase in discovery probability was only 10% when the area was 400×400 m^2.

3.3.3 Time Analysis

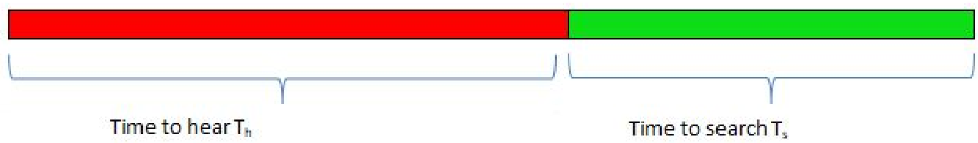


Figure 3.4: Time to hear and time to search

As indicated in Section 3.1.2, the average discovery time can be split in two components:

(i) the time T_h required to hear the communication parameters of the destination (either from another BSN or from the destination FPAN itself)

(ii) the time T_s required to actually hear a beacon from the destination FPAN after knowing the right frequency.

To get more detailed insight into these numbers, the simulations were conducted with a different settings 2.1. In these simulation, two different times

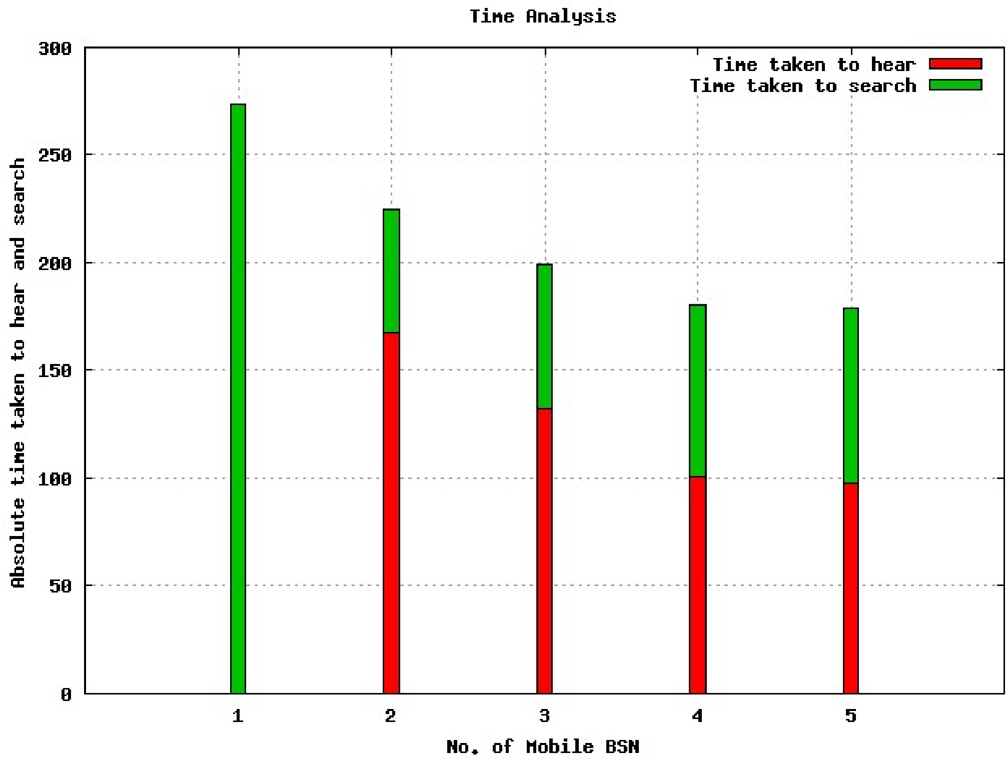


Figure 3.5: Breakdown of total discovery time T_d into the time T_h needed from beginning of search until FPAN communications parameters are known (red), and time T_s between knowing the parameters and receiving a beacon from the FPAN (green). Figure shows results for area size of 100×100 m^2

mentioned above are noted separately. There are two ways the listener can learn about the target FPAN. i.e. i) from the beacon of an other mobile BSN and ii) from the target FPAN itself.

1. If the listener hears a beacon from another mobile BSN in the network, that has the information about the target FPAN, this time is noted as time to hear T_h. At this time, the listener switches to the frequency of the target FPAN. If the listener hears a beacon from the target FPAN before the simulation time expires, this is noted as T_s.

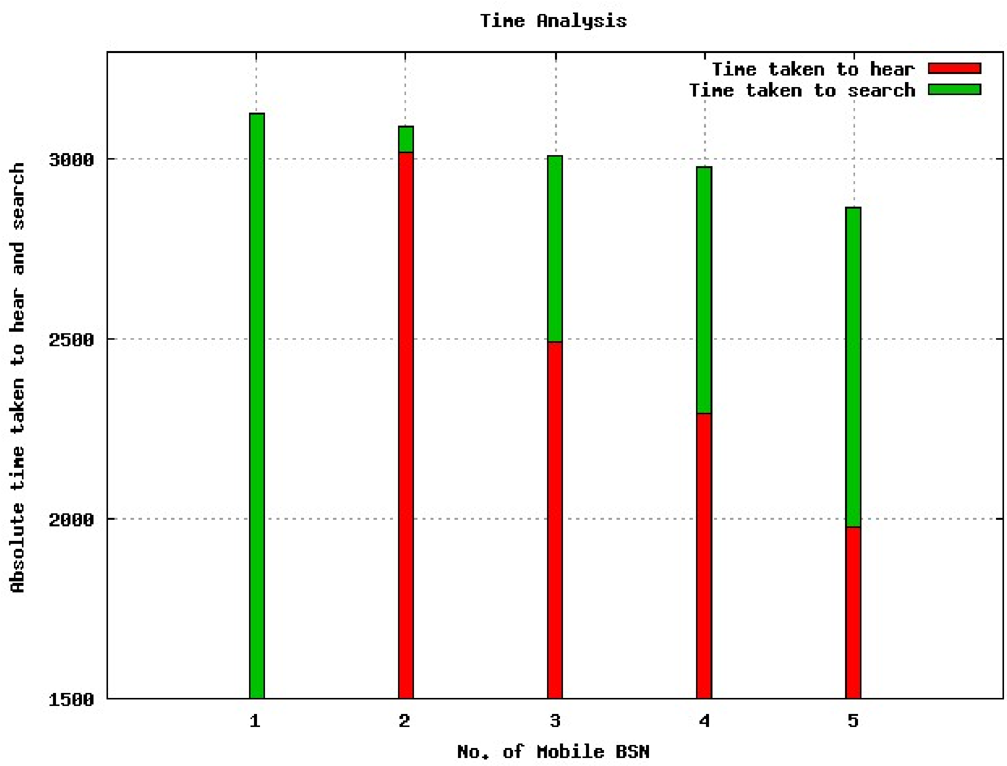


Figure 3.6: Similar to Figure 3.5 for area size 400×400 m^2

2. If the listener hears a beacon directly from target FPAN, in which case, both T_h and T_s are same.

The Figures 3.5 and 3.6 show a breakdown of the average discovery time into its two components for playground sizes of 100×100 m^2 and 400×400 m^2, respectively. The following points are remarkable:

- For both playground sizes and in case of only one mobile BSN in the network the time T_s taken to hear the communications parameters has been set to zero. This is a matter of choice.

- For the 100×100 m^2 case, it is clear the that the overall discovery time T_d indeed decreases with increasing number of BSNs. This is mainly driven by a substantial decrease in the time T_h to hear the FPAN communication parameters. With the addition of more BSNs in the network, there are more chances to hear the information about the target FPAN form another mobile BSN in the network.

However, there is also a trend that with increasing number of BSNs the T_s term increases slightly, i.e. the actual time to find the FPAN once its channel is known (often from another BSN) increases slightly. The interpretation is that with fewer other BSNs in the system the location where the searching BSN meets another BSN and learns the channel tends to be closer to the FPAN location. Being closer to the FPAN then translates into smaller values for the T_s component.

While, in the case of a larger number of other BSNs present, the information about the FPAN diffuses quickly into the network throughout the playground which reduces the time for the learner to hear T_h about the FPAN while being physically far from the FPAN. In this case, the learner, spends more time in searching the FPAN, thus increases the value of T_s component.

- Similar trends were observed for the larger playground size of 400×400 m^2. However, in this case, a significant increase in the time to search T_s is observed with the increase in the number of BSNs. This can be related to the fact that, the playground size is very large as compared to 100×100 m^2. The learner spends more time in this larger area in searching that results in the larger T_s component.

Furthermore, the Figure 3.7 presents the probability that the searching

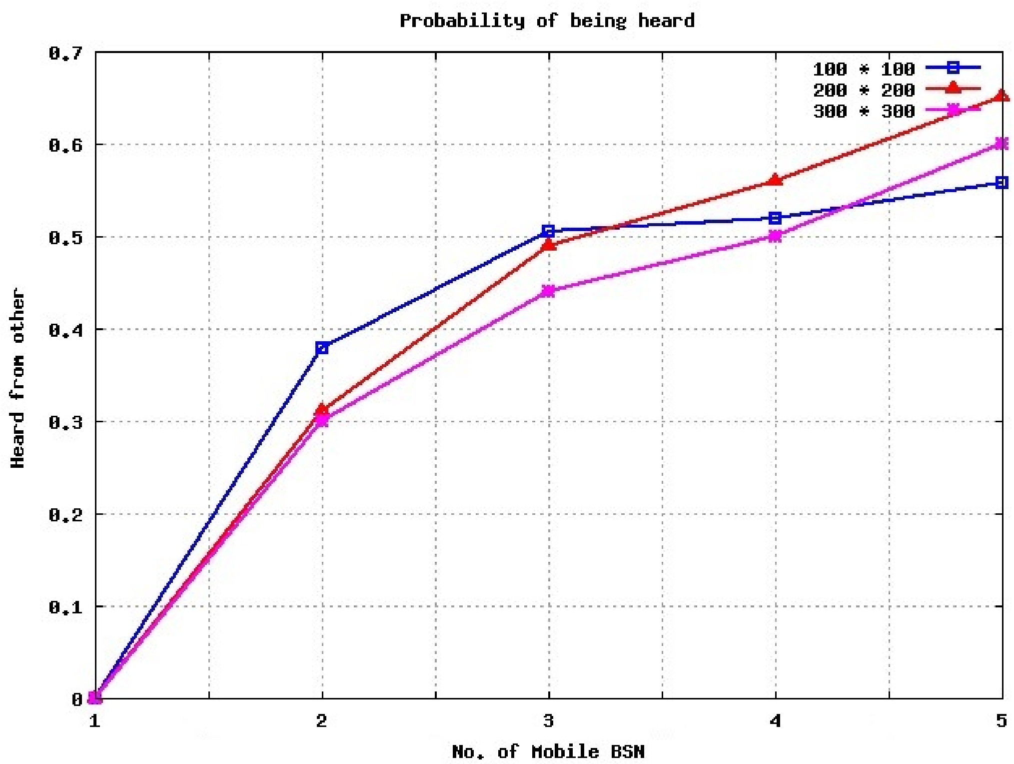


Figure 3.7: Probability that searching BSN learns FPAN channel from another BSN and not from FPAN.

BSN learns the FPANs channel from another BSN and not from the FPAN, obtained for three different playground sizes. It is important to mention here that while calculating these probabilities only the successful discovery cases were considered. The cases with unsuccessful discovery were not taken into account. Clearly, this probability increases with increasing number of BSNs, and it does not differ too much acrouss the different playground sizes.

3.3.4 Effect of Adding Another Associated Node

The performance of rumour-based scheme was further investigated by adding another associated node in each of the BSNs, both mobile or stationary. Both of these associated nodes spend the same time on each channel but are on different channels at the same time. It was expected that the "listening capacity" of the BSNs will improve with the addition of further associated nodes in each BSN, and this in return will decrease the average discovery time. To assess this hypothesis, the simulation experiments were conducted for all of the above mentioned area sizes. The average discovery times have been calculated for all the successful discoveries.

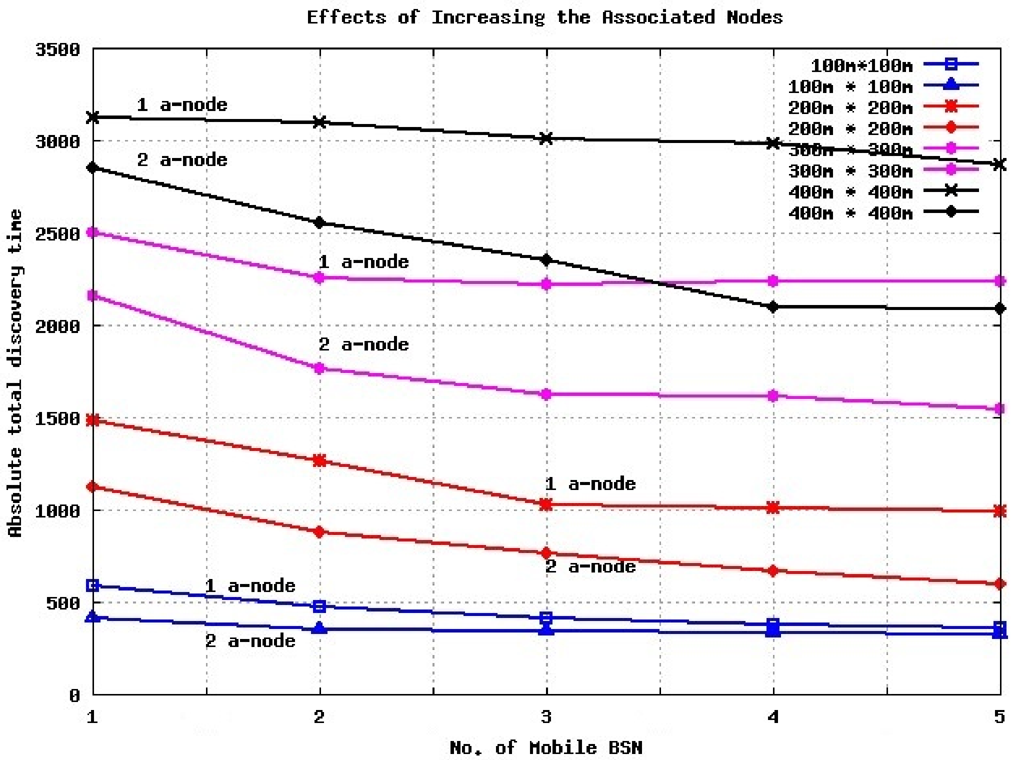


Figure 3.8: Effect of adding another associated node

The results are shown in Figure 3.8. The results shown are average absolute times until successful discovery. The simulations runs when no discovery was made were excluded from the results. The following points are remarkable:

- For each individual curve, we observed a reduction in the discovery time from nearly 9% to 44%, depending on the area size. The reduction in average time is more prominent when the area size is large.

- The average discovery time is smaller for area sizes of 100×100 m^2 and 200×200 m^2 as compared to 300×300 m^2 and 400×400 m^2.

In summary, these results clearly show that adding more associated nodes as listeners reduces the average discovery time. Furthermore, while not shown here due to lack of space, this also increases the probability of successful discovery.

3.3.5 Speed Analysis

Speed is another very important parameter of our system. The experiments were conducted to analyse how the speed of mobile BSNs affects the performance of the considered schemes. The movement speed in these experiments was chosen from two different intervals, from $2 - 8$ km/h and from $9 - 12$ km/h, so the average speed has been approximately doubled. It is important to mention that the speed ranges used in this section are different from the speed ranges used in Sections (5.1, 5.2 and 5.3). The experiments were conducted for the playground sizes 100×100 m^2 and 400×400 m^2. The impact of increasing the speed was analysed for two important performance measures i.e. average discovery time and discovering probability. The average discovery time are calculated only for all the cases of successful discovery. However, for discovery probability results, the unsuccessful discovery is also accounted for.

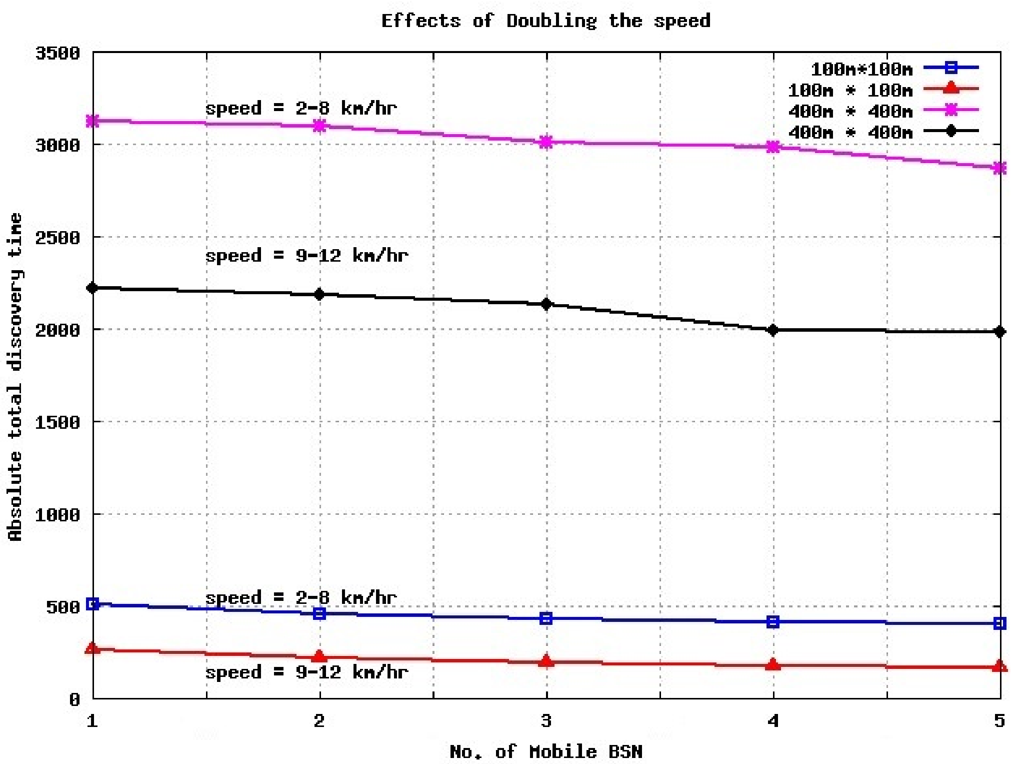


Figure 3.9: Impact of increasing the speed

The Figure 3.9 shows the results of this study. The fig shows the average (absolute) time until discovery for varying numbers of BSNs for two different playground sizes using the two different intervals for BSN speed. The following points are remarkable:

- When each of the curves is considered individually, the performance improvement when varying the number of BSNs appears to be between 10% and 15% reduction in discovery time. However, it needs to be kept in mind that these times only take successful discovery into account, and the rumour-based scheme also provides substantial advantages in terms of discovery probability.

- As can be expected, the average discovery time is generally smaller for the 100×100 m^2 playground size than it is for the 400×400 m^2 playground size.

- Perhaps more surprising is the finding that increasing the speed actually decreases the average total discovery time. This can probably be explained by the fact that with higher speeds there are on average more "encounters" between the mobile BSN and other BSNs or the FPAN.

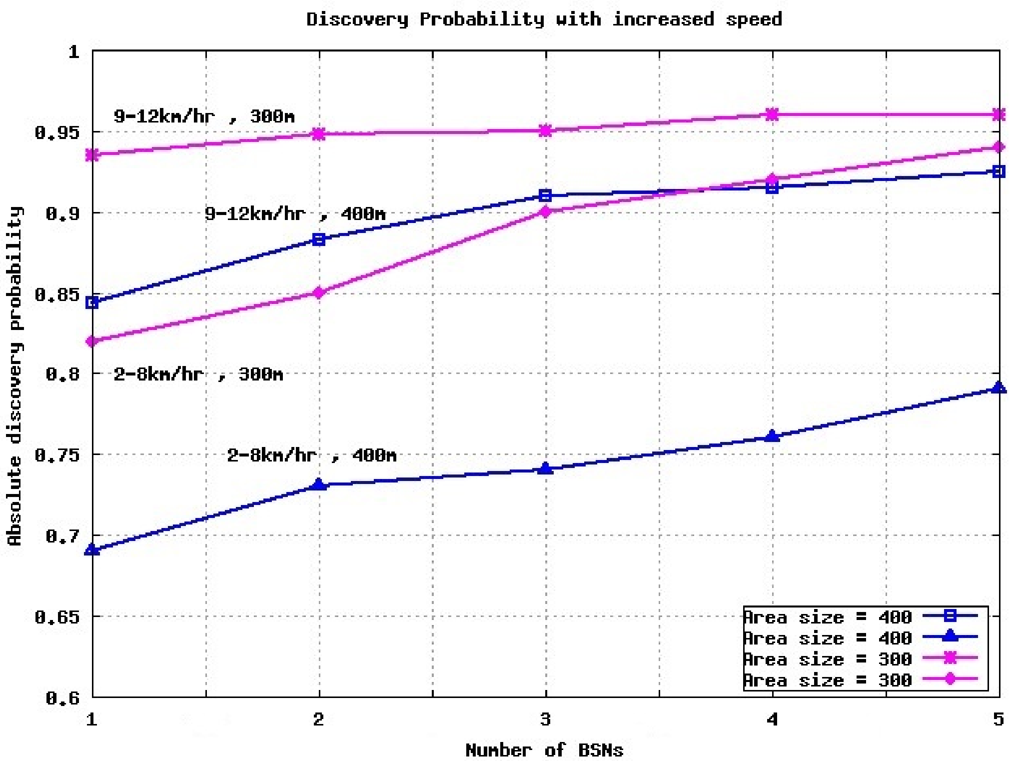


Figure 3.10: Impact of increasing the speed on Discovery Probability

From the same set of experiments the discovery probability is shown in the Figure 3.10. The discovery probability for two different playground sizes and the two different speed intervals is presented in the Fig. We have chosen

300×300 m^2 and 400×400 m^2 as playground sizes.

For the smaller playgrounds i.e. 100×100 m^2 and 200×200 m^2 the discovery probability is one for both speeds. Therefore,no interesting differences can be shown for both if these areas. The following points are remarkable:

- For the 400×400 m^2 playground size the discovery probability improves substantially for both speed values when adding more mobile BSNs. There is an increase of about 15% in the discovery probability with the increase of speed. This increase is consistent with the addition of more BSNs in the network.

  Furthermore, the case of lower speed for the 300×300 m^2 playground size shows substantial increase in the discovery probability. With the addition of second mobile BSN in the network there is an increase of about 10% in the discovery probability. However, with more BSNs in the network for the higher speed there is a smaller gain, as the discovery probability is already close to one.

- For both cases the discovery probability is larger when the speed is higher. As explained above, the suspected reason could be that with higher speeds, the mobile BSNs move swiftly that, therefore, there are more encounters between the searching BSN, the FPAN and other mobile BSNs. Due to a surge in the encounters and speedy movement of the BSNs in the network the information spreads more rapidly. This improves the chances of the listening BSN to discover the FPAN.

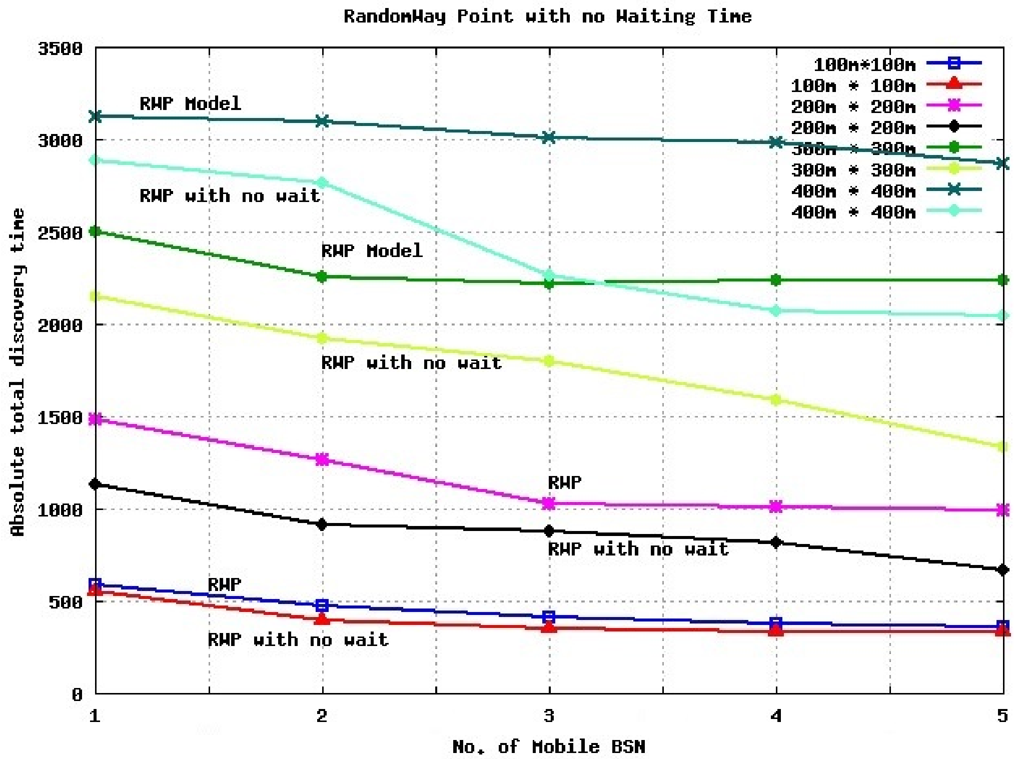


Figure 3.11: RandomWalk Model

3.3.6 RandomWay Point with No Waiting Time

To cover more ground in terms of considered mobility models, the performance of rumour-based scheme is investigated for another version of the random way-point mobility model. A mobile BSN randomly picks a point from the playground and an initial velocity. Once it reaches that point, it picks another random point in the playground and a new velocity and starts moving towards the new destination.

The difference between this model and the standard random way-point model is the random wait time once the BSN reached the destination. In other words: this model differs from random waypoint by eliminating the pause times. The mobile BSN picks the velocity from a uniform distribution between 2 km/h and 8 km/h. The experiments were conducted for all the above mentioned area sizes with the same parameters as before. The results shown in Figure 3.11 provide a comparison of our scheme for the two different mobility models, again in terms of the average absolute discovery time. This graph shows the results only where the discovery was successful. The following points are remarkable:

- For all individual curves there is an improvement in discovery time, ranging from minimum 10% to maximum nearly 40%.
- The discovery time is improved for all area sizes and this improvement is more prominent for larger playground sizes as compared to smaller playground sizes.
- The RWP-without-waiting model consistently produces better discovery times. The reason is because of the lack of waiting times more more encounters of the BSNs occur in the network which help to diffuse the information about FPAN quickly in the network.
- The efficiency of the scheme also improves more strongly as more BSNs are added, except for the 100×100 m^2 model, where discovery times are already comparably low.

3.3.7 Impact of BO

The impact of the beacon order on the average discovery time was also studied. When the playground size was 100×100 m^2, the discovery probability was maximum. For this reason we selected this area size for investigating

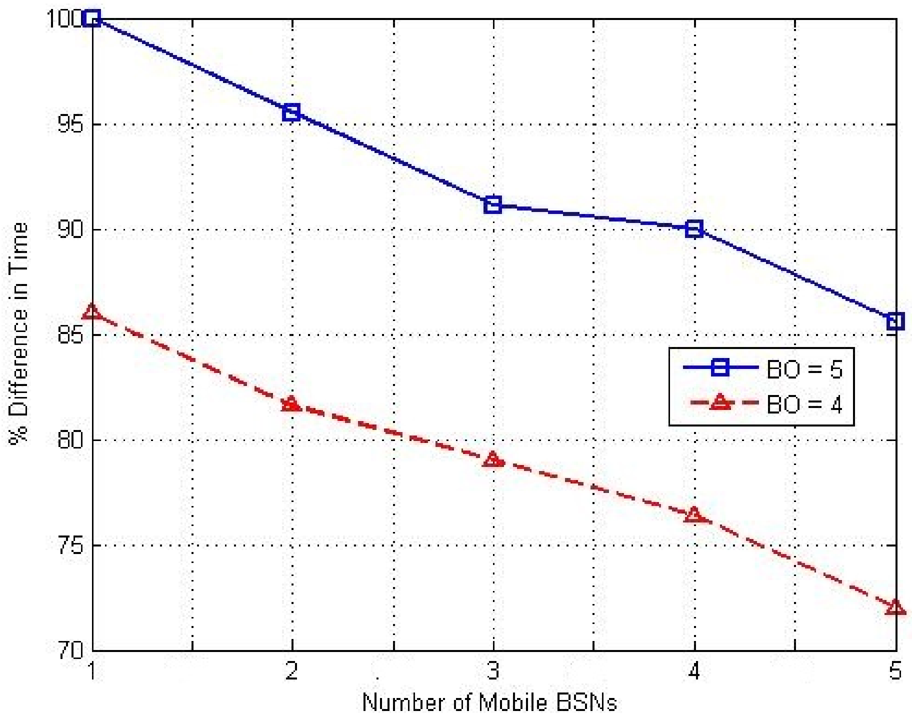


Figure 3.12: Difference in the Discovery time when $BO = 4$ and $BO = 5$

the effects of the beacon order on the performance of rumour-based discovery. The hypothesis tested was that with smaller beacon orders the average discovery time will improve. For these experiments the setting of beacon orders were modified for the networks in the system. Now all networks (fixed or mobile) are required to have the *same* beacon order BO, which for these experiments we varied between $BO = 4$ and $BO = 5$.

The results are shown in Figure 3.12. They show that for $BO = 5$ (where the beacons are transmitted with larger period) more time is required to discover the network than for $BO = 4$. However, for both beacon orders there is a considerable reduction of almost 14% in the average discovery time when the number of BSNs increases. It is worth noting that the same reduction of 14% is constant across all the number of BSNs introduced. The results supports our hypothesis.

Chapter IV

ONRECT: Background, Related Work and System Model

4.1 Background

This section presents a brief background on opportunistic routing and the ORWAR scheme. ORWAR scheme is used as a baseline for comparison.

4.1.1 Wireless technologies

There are many candidate wireless technologies that can be deployed for the implementation of opportunistic networks, for example the IEEE 802.11 WLAN standard. Many of these available standards can be used for the purposes of this work, however, for this work, no strong assumptions were made about the services of the underlying wireless technology. The key properties of wireless standards which might influence the performance of the schemes considered in this work include the data rate, transmission range, and the delay for neighbour discovery.

For this work, the IEEE 802.11 wireless technology was considered. The IEEE 802.11 standard (also known as Wi-Fi) offers amongst other things a range of different physical layers which all use essentially the same MAC protocol. There are nine 802.11 network PHY standards available for use. The first version of IEEE 802.11 was released in 1997 as *802.11-1997*. This version offered 1-2 Mbits data rate. Many other versions and amendments were released in the later years.

Out of the available physical layers standards, for this work IEEE 802.11g was considered. This version was released in Jun 2003. It operates in 2.4 GHz ISM band and supports data rates between 6 Mbit/s and 54 Mbit/s using OFDM transmission, and 2 Mbit/s when using direct-sequence spread spectrum (DSSS).

To better highlight the impact of scheduling decisions when a node has many messages in its buffer and has only limited contact time with neighbouring nodes, this work considered slowest data rate offered by IEEE 802.11g, that is, 2 Mbit/s. Furthermore, it is also assumed that the transmission range is limited to 20 m.

4.1.2 Contact Time and Remaining Contact Time

Contact time is defined as the time duration from the time when the mobile nodes moves towards each other and build a communication link until the time when they move out of the range and the link is dropped [44]. At any time instant during the contact time, the *remaining contact time* can be defined as the time duration left until the both nodes lose contact with each other. It is important to mention here that the contact time and remaining contact time in general have different probability distributions.

Contact time is one of the factors that can potentially affect the performance of opportunistic networks. This duration depends upon how long the nodes remain in each other's communication range and how long the contact lasts. In other words, the contact duration and data transfer depend highly on the mobility patterns of the nodes in the network.

The contact duration defines the amount of data that can be transferred [43]. The studies in [64] and [13] show that the distribution of the contact duration for human mobility follows a power law distribution.

4.1.3 The ORWAR Scheme

Most of the research work on opportunistic network involve the metric of *intra-contact time* [67]. *Intra-contact time* is the time between successive communication contact between two nodes. However, the remaining contact time has not been widely considered as a factor in opportunistic networking. The only work which uses this is idea[55], the *Opportunistic DTN Routing with Window-aware Adaptive Replication (ORWAR)* protocol. Unlike other peer protocols [45][6][38] [17], the design consideration for ORWAR does not include the global knowledge of the network to make the scheduling decisions. However, each node in the network is inherently aware of its location and mobility parameters like speed and direction of movement.

The ORWAR scheme uses Spray-and-Wait (SnW) [59] as a baseline scheme to control the message replication. In SnW message replication, a source node *sprays* a number L of replicas of the message by replicating it to other nodes, so-called relay nodes. In plain SnW the source node picks $L-1$ distinct relays and each relay keeps the message until it can deliver it directly to the final destination (wait state) or a time-out occurs.

In binary SnW the source node replicates the message itself and an allowance of $L/2$ further replicas to the first relay it meets. Both the source and the first relay then hand over the message and allowances of $L/4$ replications to the next relays they meet. This process of splitting continues until the source or any relay has only an allowance of one message left. Again the relays try to deliver the message to the final destination or throw it away after a time-out. ORWAR is built on the binary SnW scheme.

The ORWAR scheme differentiates messages on the basis of a user-assigned priority. Unlike SnW, ORWAR adopts a different approach while choosing the initial number L of message copies. The messages with higher priority have a higher number of message copies as compared to lower priority messages. The messages are stored in a buffer according to the utility-per-bit ratio, which is defined as the ratio of the message priority and the message length in bits.

ORWAR estimates the contact time as follows:

$$t_{cw} = \frac{2 \cdot \min\{r_1, r_2\} \cdot \cos\alpha}{\|\vec{v}\|} \tag{4.1}$$

where r_1 and r_2 are the transmission ranges of the two involved nodes, $\mathbf{v}$ is the difference vector of the velocity vectors of both nodes, $\|\mathbf{v}\|$ is its (euclidean) magnitude, and α is the angle between the nodes while they are in contact.Once the time is calculated, the messages with higher utility per bit ratio and a size that is small enough to be successfully transmitted during the contact time are replicated to the other node.

4.2 Related Work

Routing in the opportunistic networks follows an entirely different pattern when compared to the traditional wireless ad-hoc networks. Most common protocols are replication-based. Replication protocols aggressively replicate messages at every contact opportunity to minimize the delivery delay.

Epidemic routing was the first routing protocol designed specifically for the networks where there is no end to end or pre-existing network infrastructure path between the source and destination devices. Therefore, the epidemic routing protocol [62] is considered as the base line replication protocol. Epidemic routing was designed to maximize message delivery probability, minimize message latency and to minimize the resources required for successful message delivery.

Every node in the network maintains a list of messages that it has generated or has been relayed to it. The nodes maintains a table of these messages. Each message in this table is indexed with a unique identifier. Each host also maintains a summary vector to indicate the entries set in the local hash table. In addition to this, the epidemic protocol keeps record of hop count, ACK request and source and destination information in the header of the message.

When two nodes come in communication range of each other, they exchange their summary vector to analyse and obtain the messages they have not seen i.e. which are not common in either of their lists. However, any node can deny receiving a message if the TTL value is expired or the hop count has reached to maximum and it can only be delivered to the destination node only or if the receiver's buffer is full and there is no more space to accommodate the message. The epidemic routing can adopt any buffer management policy, for example, the simplest one if LIFO (last in, first out)

The epidemic routing protocol meet the goals in terms of message deliver probability and message latency. It is the fastest in terms of message delivery delay; however, it does not perform very well in terms of the resources used for successful delivery. Epidemic routing aggressively replicates the messages to achieve the goals of latency and delivery probability. Such flooding of messages exhausts the network resources and degrades the performance of the network.

Spray and Wait (SnW) [59] is one of the baseline schemes that presented the idea of "controlled replication. The main idea behind the *Spray and Wait (SnW)* is to control the total number of message replicas/copies produced in the network while maintaining the better performance in terms of delivery probability, message latency compared to other single/multi-copy and flooding based schemes. SnW is also scalable and maintains its performance according to the size of the network.

SnW comprises two phases: i) spray phase: For each message that is generated in the network, only a limited number of the message copies are sprayed to the distinct nodes in the network. Initially, the number of message replicas is equal to the 10% of the total number of nodes in the network. ii) Wait Phase: If one of the distinct nodes is not a destination node for the message, then the nodes carrying the message replicas will only forward the message to the destination.

Binary Spray and Wait (BSnW) is another version of SnW. In BSnW, the source starts with a predefined number of message copies. When this node encounters another node, it relays half the number of message copies to the other node and keep half to itself. When there is only one copy left, this copy will be transferred to the destination node.

SnW performs better as compared to epidemic routing and other routing schemes in terms of number of transmissions and delivery delays.

Smart Replication [58] or "utility based replication" strategies use a fixed number of message copies for routing.

There are routing protocols that try to optimize the performance with improved routing schemes. RAPID [6] discusses the routing of messages as a resource allocation problem under the constraints of limited buffer and bandwidth.

RAPID is a controlled replication protocol that derives a per-packet utility to replicate a packet. RAPID translates the routing metric to derive this per packet-utility. The routing metric is derived from the meta data about the

RAPID exchange the information about the network stats among nodes. The network stat information exchanged over this channel is the metadata that includes the number and location message copies and average size of the past transfers. The It used an in-band control channel that consumes minimal bandwidth.

Global knowledge Based Scheduling and Drop(GBSD) & *History Based Scheduling and Drop(HSBD)* [38] presents two different policies for a joint scheduling and buffer management algorithm. Both GBSD and HBSD are utility based scheduling schemes.

The first policy, GBSD, provides an ideal theoretical framework that serves as a reference to measure the performance of the other policy HSBD.

GBSD derives a per-message utility based on the global knowledge of the network. GSBD requires the number of replicas of each message in the network. This global knowledge is difficult to implement in the real time.

History based scheme (HSBD) adopts a statistical history based learning approach to learn the global knowledge of the network. HSBD uses this historical data to estimate the current state of the network. This exchanging information over the in-band channel for the estimation of parameters (number of replicas m and number of nodes that have seen the message n) required to derive the utility.

Global History-Based Prediction (GHP) [17] is another framework similar to the HSBD. This framework implements four different modules for message scheduling and buffer management.

4.3 System Model

4.3.1 Node Population

We consider a simple scenario which consists of 1,500 nodes, both mobile and stationary. All nodes are placed in a "playground" which resembles parts of Helsinki, Finland. The size of playground is $3500 \times 4500\ m^2$.

The nodes are divided into three groups of 500 nodes each.

- The first group comprises stationary nodes that serve as the message destinations. These nodes can represent, for example fixed wireless access points in homes or in different buildings across the city. These nodes can also generate messages and can act as relays for the messages. The destination nodes are placed randomly and independently on the playground according to a uniform distribution.

- The remaining two groups of nodes are mobile, representing cars and trams moving with varying speeds, where cars have higher average speeds as compared to trams. The nodes speeds of the cars are chosen randomly from 10 - 50 km /hrs and the speed of the trams are chosen from 10 - 40 km/hr. The nodes in both of these groups can generate and relay messages but they cannot be the destination nodes.

4.3.2 Mobility Model

Since the mobile nodes represent vehicles on roads, we use the *Shortest Path Map-Based movement Model (SPMBM)*. SPMBM initially puts the nodes at random locations on the roads. A node then selects a random destination on some road and calculates the shortest path to the destination (only on roads) using Dijkstra's shortest path algorithm.

It then picks a speed from a uniform distribution between a designated minimum and maximum speed (which are specific for the type of mobile nodes the node under consideration belongs to). Every time the node reaches the next way-point in the path (e.g. when entering a new road), it picks up a new speed from the uniform distribution and moves at that speed. Once the node reaches the destination, it picks a new destination point on the map and repeats the process [35].

This work assume that each node is equipped with GPS. The map data is stored in the *Well Known Text (WKT)* format, which is used mostly for Geographic Information System (GIS) applications.

4.3.3 Channel Model

We consider the unit disk model [24] as channel model, i.e. a device has a certain transmission radius. The transmission radius for all the nodes in this work if 20 meters.

4.3.4 General Network Settings

It is assumed that nodes have unlimited buffer capacity, where they can store unlimited messages. The message format is shown in Figure 4.1.

- Source and Destination Ids: It contains identifiers for the source and destination node of the message. It is assumed that the identifiers encode the geographical location of source and destination node.

- Message id: The message-id is unique for each new message generated by a particular source node.

- TTL Value: The Time-To-Live (TTL) field specifies the remaining time for which a message is valid before it is to be dropped. For this work, however, the TTL value is set to a sufficiently large number to ensure that no time-out occurs within the simulated time of four hours.

- Message Size: Finally, the size field specifies the size of the message. For reasons of simplicity messages are not fragmented.

Furthermore it is assumed that all of the nodes are using the same wireless technology (IEEE 802.11g with 2 Mbit/s transmission rate) for message transmission. Each of the nodes in the network has one network interface and all nodes use the same transmit power. However, to focus on message scheduling and to keep simulation times bounded we have chosen not to add a MAC layer model to the ONE simulator.

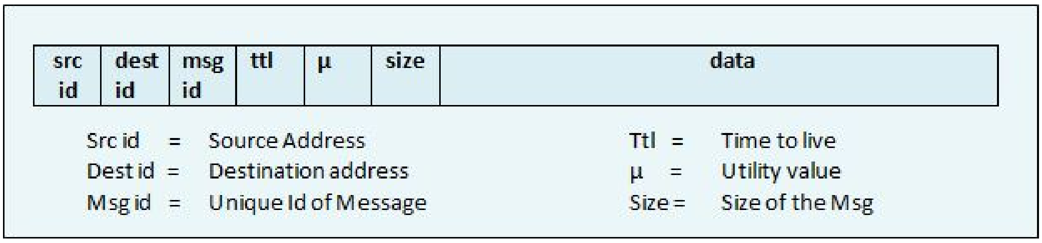


Figure 4.1: Message Format

Chapter V

ONRECT: Algorithm and Performance Analysis

The *ONRECT* scheme is a routing and scheduling algorithm for delay tolerant networks that uses controlled replication and knowledge of the remaining contact time left towards a chosen neighbour for message scheduling. The controlled replication strategy used is binary Spray and Wait [59]. It is important to note that this work do not attempt to *estimate* the remaining contact time but the nodes use their knowledge of the paths taken to obtain the real remaining contact time. By this, the nodes assess the benefits of having remaining contact time information in isolation.

Each message in the network is assigned a utility value

$$u \in \{1, 2, 3\}$$

where one refers to the lowest priority and three to the highest priority. The priorities are assigned to messages in round-robin fashion. This utility is used to prioritize the messages in the sending queue.

Each node in the network maintains a sending message queue. The messages in the sending queue are arranged according to their utility-per-bit ratio, i.e. for message m,

$$\text{Message Utility} => u_m/s_m$$

where u_m is the priority of this message and s_m its size in bits.

The messages that are generated by the node itself or received from other nodes are introduced into the sending queue at their respective place according to the utility-per-bit ratio, ties are broken randomly. The message with the highest utility-per-bit ratio is at the top and is first to be forwarded/replicated.

Furthermore, a node maintains for each message m its current replication counter L_m as per the binary SnW scheme. The initial L_m value for a freshly generated message may depend on its priority, but for the purposes of this work the same value L_0 is chosen for all priorities.

In general, a node can be connected with several other nodes at a given point in time. Therefore, each node maintains a table of all the nodes it is in contact with and the respective remaining contact time with those nodes.

From the remaining contact time toward a neighbour node j, a node i can derive the amount of data that may be transferred during this time from the characteristics of the underlying wireless technology. Node i refers to this table every time it needs to make a scheduling decision.

5.1 Calculation of Remaining Contact Time

The section explains how ONRECT calculates the remaining contact time between two nodes i and j. We assume that we know the entire path taken by the two nodes, where each path consists of a sequence of line segments taken at different velocities. We first describe the contact time calculation when assuming that both nodes move on straight lines forever, and then explain how we take account of changes in direction and speed. For simplicity we restrict to the two-dimensional case, generalization to three dimensions is straightforward.

5.1.1 Two Nodes Moving on Straight Lines

Suppose two nodes i and j with velocity vectors $\mathbf{v}_i$ and $\mathbf{v}_j$ and initial positions $\mathbf{x}_i = (x_{i,0}, y_{i,0})$ and $\mathbf{x}_j = (x_{j,0}, y_{j,0})$, respectively. We transform the problem to assume that node i is stationary and located at the origin (position $(0,0)$), whereas node j then moves with velocity vector $\mathbf{v} = (v_x, v_y) = \mathbf{v}_j - \mathbf{v}_i$ and starts at initial position $\mathbf{x}_0 = (x_0, y_0) = (x_{j,0} - x_{i,0}, y_{j,0} - y_{i,0})$. Let $\mathbf{p}(t)$ be the position of node j at time t, i.e.:

$$\mathbf{p}(t) = \begin{pmatrix} x_0 \\ y_0 \end{pmatrix} + t \cdot \begin{pmatrix} v_x \\ v_y \end{pmatrix}$$

then the distance of node j to node i is given by its distance to the origin, i.e.:

$$\|\mathbf{p}(t)\| = \sqrt{(x_0 + t \cdot v_x)^2 + (y_0 + t \cdot v_y)^2} \tag{5.1}$$

When $R > 0$ denotes the mutual transmission range of i and j, then we seek values of t for which $R = \|\mathbf{p}(t)\|$ holds – this leads to a quadratic equation.

When no solution exists, node i and j never get in range and their contact time is zero. When two solutions $0 < t_1 < t_2$ exist, then node j has started outside the range of i, then comes close enough to i for time $t_2 - t_1$ and then leaves again.

When only one solution exists, two cases are possible: the first one is that j's starting position was outside i's range, then j's trajectory just touches the circle of radius R around i and the contact time is zero. The second case is when node j's starting position is located within the range of i and leaves it at some time $t > 0$, then the contact time is t.

In these considerations it is implicitly assumed that $\|\mathbf{v}\| > 0$ holds. In the border case where $\|\mathbf{v}\| = 0$ and thus $\mathbf{v} = 0$, the contact time is either zero (when $\|\mathbf{x}_0\| > R$) or infinity (when $\|\mathbf{x}_0\| \leq R$).

5.1.2 Contact Time over Paths

In this set up two nodes normally don't move on straight lines, but follow a (shortest) path on a street network, i.e. they change direction when entering a new street, and change their speed. Suppose node i moves along a path

$$(\mathbf{x}_{i,1}, \mathbf{x}_{i,2}),\ (\mathbf{x}_{i,2}, \mathbf{x}_{i,3}),\ \ldots,\ (\mathbf{x}_{i,k-1}, \mathbf{x}_{i,k})$$

and node j along path

$$(\mathbf{x}_{j,1}, \mathbf{x}_{j,2}),\ (\mathbf{x}_{j,2}, \mathbf{x}_{j,3}),\ \ldots,\ (\mathbf{x}_{i,m-1}, \mathbf{x}_{i,m})$$

where each $(\mathbf{x}_{a,b}, \mathbf{x}_{a,b+1})$ denotes a line segment. On each of the line segments $(\mathbf{x}_{i,b}, \mathbf{x}_{i,b+1})$ on its path node i has speed $v_{i,b}$, similarly for node j. The times where node i changes directions (moving to the next line segment) are given by $t_{i,b}$, similarly for node j.

In short, the algorithm proceeds by sorting the times $t_{i,b}$ and $t_{j,b}$ in ascending order to get times $t_1, t_2, \ldots, t_{k+m}$. Then the "straight-line" computation described above is applied to each of the time intervals $[t_i, t_{i+1}]$ (keeping track of the positions of both nodes) and sum up the results. When the "straight-line" contact time for some interval $[t_i, t_{i+1}]$ extends beyond t_{i+1}, then the contact time is clipped.

5.2 Vaccination Mechanism

The vaccination mechanism is used both in ORWAR and ONRECT, its main purpose is to stop further propagation of messages that have reached their final destination, to limit the effort spent by the network. Broadly speaking, the information that a message has been received is flooded into the network and all existing copies of the message are then dropped.

In detail, each node maintains a list of messages id's m_d that have been delivered to their final destinations. Whenever two nodes come in contact with each other, they exchange their lists. Both of the nodes then update their sending message queues (m_q) using these lists by dropping any message that has been mentioned in m_d.

Once a message is delivered to the final destination node, an acknowledgement message is sent back to the sending node. When this vaccination message is transferred from one node to another node, the id of the message is added to the delivered message queue m_d at both sending and receiving queue.

5.3 ONRECT Algorithm

The ONRECT message scheduling decision depends on multiple factors:
(i) remaining contact time
(ii) the best neighbour to forward the message to (in particular, we only consider neighbours which have a destination that is within 700m of the message destination, and from these we pick the one that gets closest), and
(iii) the position of the message in the queue (the message with higher utility-per-bit will have higher position).

The pseudo-code for the algorithm is given below:

```
========================================
For each node $i$:
 Variables
 $x_i, y_i$    current location of the node
 $X, Y$        Next waypoint of the node
 $\vec{v_i}$   node speed if it is not stationary
 $R_i$         Wireless transmission range of node
 $m_s$         size of a message m
 $L_k$         number of message copies
 $s_{max}$     maximum data that can be transferred during
               calculated remaining contact time
 $m_q$         Sending message queue (message are stored in $u_k/m_s$
               order )
 $m_d$         Message id's list that are delivered to the final
               destination
 connTime  table to maintain the remaining time (in terms of
           maximum data that can be transferred during this
           time, stores the $s_{max}$ value) with the other nodes
=========================================
A node $i$ comes in contact with other node j:

send $m_d$ to j     // send delivered messages list to j
receive $m_d$ from j     // receive delivered messages list from j
update $m_q$     // delete all messages that have been delivered

/** Compute the remaining contact time and add in the
connTime table **/
connTime.add($calculateTime(nodeId)$)
=========================================
/** Assuming that this node is connected with multiple nodes **/
/** Direct Delivery Message **/

For each message m in $m_q$:
    if $m_s < s_{max}$ of destination node:
    deliver m to the destination node
    if m.ack:
```

```
        Remove the messages from the m_q and add the message id in m_d
        update connTime:
        s_max = s_max - m_s
/** Rest of the messages **/
For each message in m_q:
   //Find the best neighbor
    bestNeighbor = neighbor(message m)
    if s_max > m_s ⋀ L_k > 1:
        transmit m to bestNeighbor
        L_k = L_k/2
        in connTime for bestNeighbor:
        s_max = s_max - m_s

calculateTime(nodeId):
    get (x_i, y_i),(X,Y) and v_i
    compute remaining time
    calculates s_max
    return s_max
neighbor(message m):
    List Nodes = getAllConnectedNodes()
    foreach(Node otherNode:Nodes) {
        if(otherNode.finalDestination < m.destination){
            return otherNode

      }
   }
```

The ONRECT algorithm shares many similarities with ORWAR, however, the key difference is in the scheduling algorithm: in ORWAR considers one neighbour and then send all the message to it in order of their utility-per-bit ratio and as long as it can (i.e. as long as the remaining contact time does not expire), whereas in ONRECT considers all possible neighbours for each message and pick the best one. ONRECT makes a choice of the best neighbour by choosing the neighbour whose current destination is closest to the message destination while ORWAR just transfers messages to any node that comes in range.

5.4 Performance Analysis

For this thesis, comprehensive simulations were performed to evaluate the performance of the ONRECT algorithm in comparison with ORWAR and SnW. Different message sizes were considered for this purpose. For each message size a sufficient number of simulation replications have been carried out to obtain a relative confidence interval width of 5% at a confidence level of 95% for the delivery probability. Each replication considers a different placement of stationary and mobile nodes, message generation times and message destinations.

The results were compared with the results from the two other algorithms, binary Spray and Wait [59] and ORWAR [55]. These protocols are run with similar settings as ONRECT to compare the results. The values for the fixed parameters are summarized in Table 5.1.

Aside from the vaccination algorithm, there are two major differences between ONRECT and ORWAR:

- the contact time calculation (using Equation 4.1 for ORWAR and the algorithm from Section 5.1 for ONRECT)
- the neighbour selection scheme.

To analyse the impact of the contact time calculation, we have introduced two variations of the considered schemes: the ONRECT- scheme is very similar to ONRECT but uses the estimated contact time information according to

Parameter	Value
Number of Message Copies L_k	6
Time to Live	1000 minutes
Buffer space	infinite
Speed of the Cars	$10 - 50$km/hr
Speed of the Trams	$10 - 40$km/hr
Number of Host Groups	3
Number of Hosts per Group	500
Message generation interval	1-10 sec
Number of wireless interfaces	1
Interface Transmit speed	2 Mbps
Maximum Message Size	10 KB

Table 5.1: Simulation parameters settings for all the protocols

Equation 4.1, whereas the ORWAR+ scheme is very similar to ORWAR but uses the contact time calculation from Section 5.1.

5.5 Simulation Setup

All algorithms were implemented in the Opportunistic Network Environment (ONE) simulator version 1.5 [35]. This simulator is specifically designed to simulate algorithms and protocols for opportunistic networks, and in fact ONE is a popular tool in this area. Many commonly known opportunistic network protocols and algorithms like Spray and Wait, Epidemic Routing, or PRoPHET are available as a part of ONE. The simulated time for each replication is 4 hrs. The experiments were conducted for three different message size ranges. Small sized messages are drawn randomly from the interval between 200 Bytes and 400 Bytes, medium sized messages have a size between 1 KB and 2 KB, and large sized messages are between 5KB and 10KB. The messages are generated every 5 - 10 seconds in the network following a uniform distribution.

5.6 Results

5.6.1 Average Delivery Delay

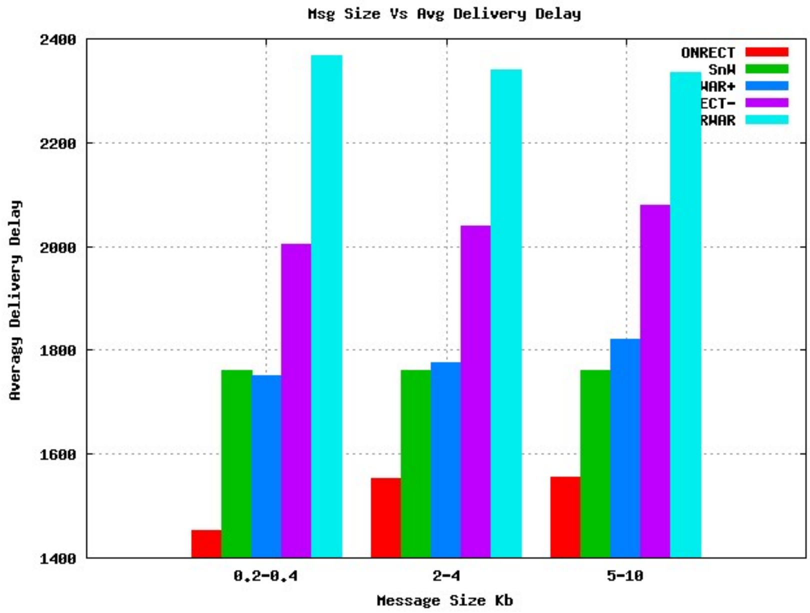
One of the most important performance measures in this work is the average delivery delay, defined as the delay (in seconds) between message generation and its first reception at the intended destination (computed only for those messages which actually have reached the destination).

Figure 5.1a shows the average delivery delay for different message sizes.

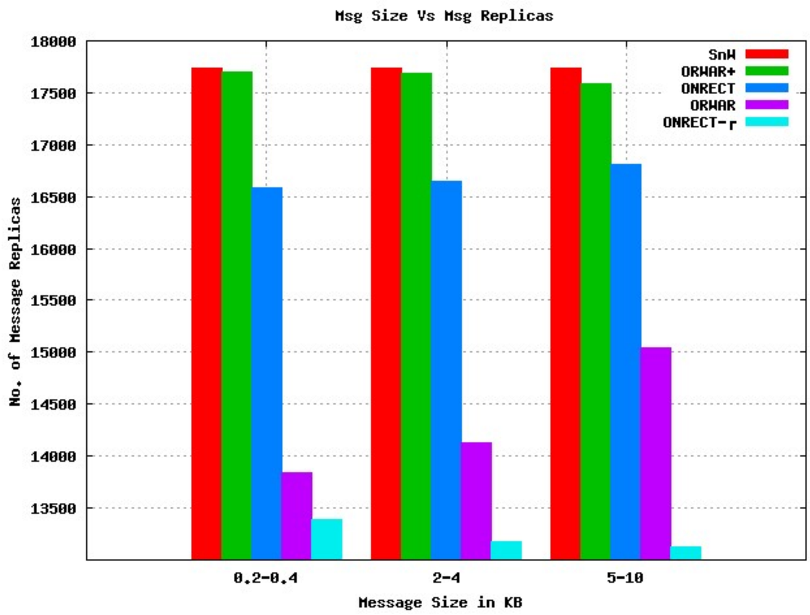
There is a substantial gap in the average delivery delay of ORWAR and ONRECT. It is obvious that the ONRECT algorithm incurs the smallest delays as compared to ORWAR and SnW. ONRECT incurs nearly 42% less delay than ORWAR and nearly 18% less delay than SnW.

To understand whether this performance difference is due to the availability of the real contact time to ONRECT or due to ONRECT's scheduling algorithm, we have also included the results for ONRECT- and ORWAR+. Interestingly, ONRECT offers still significantly better delivery delay than ORWAR+, so the availability of real contact time information does not fully explain the difference between ORWAR and ONRECT.

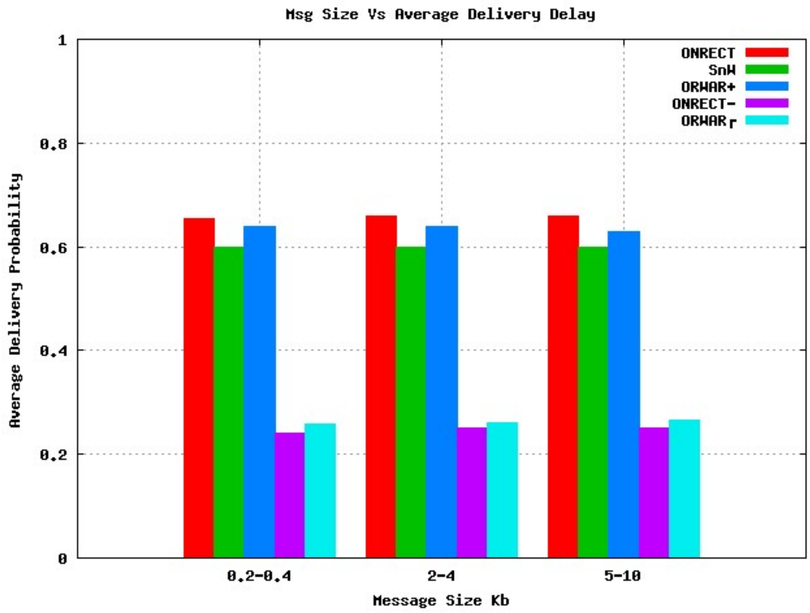
To our surprise, however, it can be seen that ONRECT- performs significantly worse than ORWAR+, which suggests that the neighbour selection scheme of ONRECT is susceptible to the error in the remaining contact time calculation introduced by ORWAR's estimator. It is a subject for future work to better understand this behaviour.



(a) Average Delivery Delay



(b) Comparison of the 'Effort' in terms of Message Copies



(a) Average Delivery Probability

Figure 5.1: Graphs

5.6.2 Number of Message Replicas

An important performance measure is the overall effort required in terms of the number of times a message is replicated between nodes for successful delivery. The Figure 5.1b reports the total number of replications created by all messages generated during simulation time.

The results suggest that the contact time estimation of ORWAR (which does not account for turns) leads to a reduced number of message replications. A possible explanation for this is that ORWARs estimator tends to underestimate the contact time, and so this estimator allows fewer messages to be transmitted during contact.

The difference between ORWAR and ONRECT- (and similarly between ORWAR+ and SnW on the one hand and ONRECT on the other hand) can likely be explained by the selection rule of ONRECT-, which only allows replications to neighbours that come within a certain range of the message destination.

ONRECT requires less effort in terms of message replicas. It is clear from the results that the ONRECT algorithm produces nearly 7% - 10% less message copies as compared to SnW. The number of message replicas decrease for ONRECT- because the the times estimation is pessimistic and also the the message replication is controlled by neighbour's choice.

But achieving a deeper understanding of these differences is a possible subject of future work.

5.6.3 Average Delivery Probability

The average delivery probability is another important performance measure of this work. This probability is defined as the percentage of generated messages which are successfully received by their destination within the simulation time.. The results are shown in fig 5.1a.

The delivery probabilities of SnW, ONRECT and ORWAR+ are at about the same level and very different from the delivery probabilities of ORWAR and ONRECT-. The average delivery probability of ONRECT is far better than ORWAR. This suggests that both ONRECT and ORWAR are substantially influenced by the accuracy of contact time information available to them while, SnW is independent of this information and requires more message replications.

Also, ONRECT replicates the messages towards their final destination by selecting the neighbour which gets closest to the intended destination, which also improves average delivery probability. On the other hand, though SnW uses controlled replication, it replicates more message copies in the network in all directions.

Chapter VI

Conclusions

In the first part of this work a cooperative passive discovery scheme called 'rumour-based scheme' for IEEE 802.15.4 based networks is presented. The performance of rumour-based scheme was compared with the basic, uncooperative scheme based on sweeps. It is shown that rumour-based scheme significantly reduces the discovery time of the fixed FPAN, at the cost of some cooperation between mobile BSNs. With more mobile BSNs present, the necessary information can disperse more quickly. With this information being available from more sources, the discovery time of the network improves significantly by giving the searching BSN an early hint about the right frequency. It is also observed that with the increase in the number of BSNs the discovery probability also improves. Similarly, when the area size becomes smaller, the discovery probability increases as well. Furthermore, with increasing number of BSNs the discovery time reduces drastically. On the contrary, with a large sized playground, say $300 * 300m^2$ or $400 * 400m^2$, the discovery time reduces with the increase in number of BSNs. We also observed the effects of beacon order on discovery time. The small BO as shown in Figure 6 proved to be more beneficial as they ensure a small discovery time.

The effects of increasing the speed on the discovery time were also investigated for different playground sizes. The experiments concluded that increasing the speed is more helpful in huge playground sizes where the nodes are located far across each other. In this case more speed helps in a quick discovery. Also, the experiments were conducted to synthesize the discovery time into two constituents i.e. time required to hear about the communication parameter of the destination and time required to actually discover the destination. The results show that with the addition of each new mobile BSN in the network, the time required to hear about the network decreases and that also reduces the overall time for discovery. Furthermore, it was observed that the difference in discovery time when the frequency of the destination is known to the searching BSN. The experiments show that if destination frequency is known to the searching mobile, the discovery time is decreased. However, this decrease vary for different playground sizes.

The later part of the thesis addresses the potential impact of the knowledge of remaining contact time on message scheduling in opportunistic networks.We have introduced the *Opportunistic Networks Routing with REmaining Contact Time (ONRECT)* scheme, which incorporates the information about contact time and the destinations of neighboured nodes and the messages into scheduling decisions. Its performance is compared against the SnW scheme and the ORWAR scheme. The results show that although the average delivery probability of ONRECT and SnW are very close, ONRECT requires less effort as compared to SnW and achieves nearly the same average delivery probability when highly reliable contact time information is available. ONRECT selects a neighbour for the directional replication of the messages which means the messages are replicated in the direction of the destination of the message. In this way, the messages are better diffused in the network towards the message's destination. It is observed that the average delivery probability remains nearly constant with the increase in message size. However, with an increase in message size, the effort, in terms of number of message copies, also increases. This effort is not very prominent for ONRECT and SnW, but ORWAR shows a sharp increase. Another important observation is the small average delivery delay offered by ONRECT. The ONRECT's improved time estimation and neighbor selection results in a smaller average delivery delay as compared to other protocols.

There is some potential for future research. One important issue is to gain a better understanding of the apparent sensitivity of ONRECT and ORWAR with respect to the quality of the available contact time information, and to devise schemes which allow for more graceful performance degradation when the quality of the contact time estimate degrades. We furthermore believe that there is some potential in further optimizing the selection rule of ONRECT, and it is also interesting to assess the impact of vaccination.

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